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THE FABRICATION AND TESTING OF GLASS MATRIX COMPOSITE CYLINDERS FOR GUN BARREL LINER APPLICATIONS

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ABSTRACT

The feasibility of fabricating glass matrix composite (COMPGLAS^{TM}) cylinders for use as gun barrel liners was investigated. The system of borosilicate glass reinforced with discontinuous graphite fibers was utilized to fabricate three different composite configuration concepts by the fabrication methods of hot isostatic pressing (HIP), uniaxial creep-forming of cylindrical segments, and the machining of cylinders from hot-pressed billets. Analytical design studies performed at the Saco Defense Systems Division of Maremont Corp. indicated that the latter method, where the fibers were randomly oriented in the radial and tangential directions with no fibers in the axial direction, was the most favorable configuration.

Three cylindrical liners were diamond core drilled from the hot-pressed billet, final machined to a .50 caliber bore, assembled into metal sleeves and jackets, and test fired for a total of 10 shots single fire. Although two of the three composite liners showed evidence of a few very small circumferential cracks at one end of the bore before firing, the cracks did not grow as a result of firing. The firing tests indicated that the use of a low modulus, fracture tough, ceramic composite such as graphite fiber reinforced glass is capable of withstanding the pressure stresses resulting from firing without failure and exhibits considerable potential as a gun barrel liner.

The Fabrication and Testing of Glass Matrix Composite Cylinders for Gun Barrel Liner Applications

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SUMMARY

The feasibility of fabricating cylinders of glass matrix composite materials for use as liners for gun barrels was investigated. With the Saco Defense Systems Division of Maremont Corp. as subcontractor, UTRC studied the specific COMPGLAS™ system of graphite fiber reinforced borosilicate glass matrix composite, which has been shown in previous work to exhibit excellent strength and fracture toughness as well as excellent friction and wear properties. UTRC investigated three different cylinder fabrication concepts; three different fabrication techniques; the mechanical properties, particularly tensile and compression strength, of discontinuous graphite reinforced borosilicate glass; and fabricated three near net shape .50 caliber barrel liners with optimum fiber orientation. Maremont Corp. performed a design analysis to determine the effect of liner thickness and amount of liner/sleeve/jacket interference fit on the resultant liner stresses, machined the liners to final dimensions and assembled them into barrel assemblies, and test fired the three assemblies under single shot conditions for 10 rounds each.

The three fabrication methods investigated consisted of hot isostatic pressing (HIP) of cylinders, uniaxially creep-forming cylinder segments in shaped dies, and the machining of cylinders from hot-pressed billets. In all of the fabrication methods, discontinuous graphite fibers reinforcing a borosilicate (Corning 7740) glass matrix was utilized. The three fabrication methods lend themselves to three different composite configuration concepts which differed primarily in the direction of primary fiber orientation. While considerable work was performed on HIP fabrication, and some on creep-forming, the Maremont Corp. analytical results indicated that the machining of cylinders from hot-pressed billets where the fibers were in the radial and tangential directions, with no fibers in the axial direction, was the most favorable configuration. Accordingly, this configuration was used to fabricate the cylinder liners and to generate pertinent mechanical properties.

In the fiber configuration chosen, discontinuous graphite fibers are randomly oriented in the 1-2 plane, with no fibers in the 3 direction. For accurate analytical results to be obtained on various cylinder configurations, certain mechanical properties were determined. These included strength, elastic modulus, and failure strain for the 1 and 3 directions in both tension and compression. From this, Poisson's ratio was determined in tension and compression.

The three cylinder liners were diamond core drilled from a 4" x 4" x 4" block of hot-pressed graphite-glass composite. The as-drilled liners had dimensions of ≈0.475" ID, 0.925" OD x 4.1" long. These were then sent to

Maremont for final machining. Two of the final machined liners (configurations 1 and 2) had dimensions of 0.91" OD and a .200" wall thickness while one (configuration 3) had 0.81" OD and a .150" wall thickness. The interference fit between the liner and metal sleeve was .0005" for Config. 1 and .0015" for Config. 2 and 3. The interference fit between the sleeve and metal jacket was .0005" for Config. 1 and 2 and .0017" for Config. 3. This resulted in a calculated tangential tensile stress at the bore of the composite liner during firing of 32.2 ksi for Config. 1, 20.7 ksi for Config. 2, and 9.1 ksi for Config. 3.

After assembly of the liners into the metal sleeves and jackets, all liners were observed by Zyglo dye penetrant inspection to have circumferential cracks in the bore ~1/4"-3/4" from the muzzle end of the liner. These cracks may be connected with the nonuniformity of heating or cooling of the jacket when shrink fitting the liner/sleeve subassembly. Assembly #1 was ground back ≈1/2" to remove the observed cracks. The other two assemblies were fired with the cracks present.

Each assembly was fired for a total of 10 shots single fire. The liner bore surface was examined visually with a borescope after the 1st, 3rd, 6th, and 10th round. After firing, the bore diameter was measured as well as its surface roughness. The diameter was observed to increase slightly (up to .0002") while the surface roughness also increased somewhat. The cracks present in assemblies 2 and 3 before firing did not grow as a result of firing. In fact, the crack indication on assembly #3 before firing could not be found after firing.

In summary, the test results have shown that the use of a low modulus, tough, ceramic composite such as graphite fiber reinforced glass has considerable potential as a gun barrel liner. The material has been shown to be capable of withstanding the pressure stresses resulting from firing without failure. Even when pre-existing cracks were present, no tendency for crack growth or catastrophic failure was exhibited.

INTRODUCTION AND BACKGROUND

Current state-of-the-art gun barrels are fabricated from stellite lined chrome plated steel tubes. Due to their high percentage of the critical elements cobalt and chromium, they are becoming increasingly expensive to manufacture. In addition, new gun systems that require longer range, higher velocities, and more rapid rates of fire present erosion and wear problems that are beyond the capability of the current stellite liners.

With these limitations in mind, a study was undertaken by the Maremont Corp., Saco, Maine (Ref. 1) to attempt to use a ceramic material (Carborundum α-SiC) as a gun barrel liner. The objective of this study, funded by the Army Armament Research and Development Command, was to establish the feasibility of ceramic lined barrels under limited firing conditions by fabricating 4" long liners from α-SiC, placing these liners into metallic sleeves for assembly into .50 caliber gun barrels, and test firing these barrels under single shot conditions at RT to determine the integrity of the ceramic liner.

While some initial difficulty was encountered during the shrink fit process of assembling the SiC liners into their metal sleeves due to nonuniform heating and cooling of the components causing the development of transverse cracks near the ends of the SiC liner, the end result of this study was encouraging. A SiC liner was successfully shrink fitted into a steel sleeve and assembled into a metal jacket that allowed the assembly to be test fired as a smooth bore .50 caliber barrel under RT single shot firing conditions for a total of 1000 rounds. After this test, no evidence of SiC liner erosion was found and the ceramic liner remained crack free.

While the α-SiC gun barrel liners appear to be potentially viable, there was some concern expressed about the ability of a monolithic ceramic with very low impact resistance and extreme notch sensitivity to withstand actual battlefield conditions. In addition, the cost and fabrication techniques necessary to fabricate a thin walled, large diameter, relatively long length SiC liner for large caliber guns may be prohibitive. It has been determined by the Army that the real payoff for a ceramic liner would be for advanced large caliber weapons.

With the aforementioned limitations of monolithic ceramics such as α-SiC in mind, the Army Materials and Mechanics Research Center (AMMRC) awarded the present contract to United Technologies Research Center (UTRC) to investigate the feasibility of fabricating cylinders of glass matrix composite materials for use as liners for gun barrels. This class of composite materials, known as COMPGLAS™, consists of glass and glass-ceramic matrices reinforced with a variety of fibers (Refs. 2-6) including graphite, SiC, and Al_2O_3. These materials can exhibit the advantages that ceramic materials possess over metal

alloys of low density, low thermal expansion, potentially higher use temperature, and no critical elements such as Co, Cr, and Ta; and yet not exhibit the severe limitations of monolithic ceramics such as low impact resistance and extreme notch sensitivity. COMPGLAS™ materials can exhibit excellent strength (~100 ksi) and fracture toughness (K_{IC} >20 ksi$\sqrt{\text{in.}}$) and can be tailored to fit particular requirements; such as oxidation resistance to high temperatures, either a moderate or low thermal expansion coefficient, or specific properties in certain directions within an object. These materials, in particular the graphite and SiC reinforced glass composites, have also been shown to exhibit excellent friction and wear properties; an important consideration for a gun barrel application.

The processing of glass and glass-ceramic matrix composites had been confined up to this time to uniaxially hot-pressing arrays of fibers that had been infiltrated with glass powder particles. Fiber arrays have consisted of continuous fiber lay-ups in the 0°, 0°/90°, 0°/90°,±45° directions and, in the case of graphite fibers, discontinuous fibers that are randomly oriented within the plane. The latter fiber array is available in a paper form where the chopped fibers are held together with a binder. This current processing method is eminently suitable for the fabrication of flat plates, bars, and simple curved or bent shapes. However, it is not amenable to the fabriction of rings or cylinders of any appreciable length.

Accordingly, the aim of the current program was to investigate the feasibility of fabricating cylinders of COMPGLAS™ for use as gun barrel liners. Three fabrication methods were utilized; hot isostatic pressing (HIP) of cylinders, uniaxially creep-forming cylinder segments in shaped dies, and the machining of cylinders from hot-pressed billets of COMPGLAS™. These fabrication methods are described in greater detail in Section IV of this report. After the fabrication of acceptable cylinders, the Saco Defense Systems Division of the Maremont Corp., Saco, Maine was subcontracted to assemble the COMPGLAS™ liners into metal sleeves and test fire them under single shot conditions at RT.

The types of COMPGLAS™ materials available for this investigation range from rather low temperature glasses such as Corning 7740 borosilicate to higher temperature lithium aluminosilicate (LAS) glass-ceramics, reinforced with either graphite, alumina, or silicon carbide fibers. For a gun barrel liner application, where fracture toughness is a prime concern, the graphite or SiC fiber reinforced materials are much superior to the alumina composites. The temperature to be expected at the ID of the liner during the firing test, however, could very well be higher than the graphite fibers or most of the glass matrices could sustain for an appreciable length of time. Unfortunately, the SiC fibers are not available in chopped fiber form which, as will be discussed, was deemed to be necessary for successful HIP fabrication of

cylinders. It was thus decided that, for the initial fabrication studies, the firing test be limited to a minimum number of shots (10) in order to keep the time at high temperature of the barrel liner to an acceptable level. This allowed the use of chopped graphite fibers in paper form as the reinforcement for an easily formable borosilicate or aluminosilicate glass matrix. It was believed that, for the initial program effort, this type of glass composite offers the greatest chance for a successful demonstration of the concept of fabricating and using a COMPGLAS™ cylinder as a liner in a gun barrel application. Future efforts could then be directed at optimizing the fiber/matrix combination and fabrication procedure for the actual environment of operation.

GLASS MATRIX COMPOSITE CYLINDER FABRICATION CONCEPTS

The three fabrication methods mentioned in the last section lend themselves to three different composite configuration concepts, each with some advantages and some drawbacks. These fabrication concepts are shown in Fig. 1. Concept #1 could theoretically be fabricated by the hot isostatic pressing (HIP) of circumferentially wrapped plies of chopped graphite paper impregnated with glass powder around a center cylindrical mandrel. The advantages of this concept is that the axial and circumferential directions within the cylinder would be very strong and tough and no discontinuities would exist in the cylinder. The disadvantages would be that the radial direction would be very weak, since no fibers would be aligned in that plane, and that this configuration would be very difficult to actually fabricate, as will be further discussed in Section IV of this report.

Concept #2 is similar to concept #1 except that the cylinder is made up of two or more cylindrical segments bonded together. The advantages of this concept are that the axial direction would be strong and tough and the fabrication would be considerably easier than concept #1. The cylindrical segments could be fabricated by creep forming preconsolidated flat plates into the segments by using shaped dies. The disadvantages of this concept are that the discontinuities at the bond line between segments would be weak in the tangential direction and that, as in concept #1, the radial direction would also be weak.

Concept #3 would be fabricated by core drilling the cylinders out of a hot-pressed billet of COMPGLAS™ that would be made by uniaxially hot-pressing glass powder impregnated plies of chopped graphite fiber paper in simple square dies. The fibers would then lie in the radial and tangential directions which would accordingly be strong and tough. This concept would be the easiest to fabricate providing the length of the cylinder is kept rather short. The disadvantages of this concept are that long cylinders would be very difficult to fabricate and that the axial direction, i.e. parallel to the cylinder length, would contain no fibers and thus be very weak.

In order to determine which fabrication concept would satisfy the stress requirements generated during liner assembly and testing, designers at Maremont Corp. needed to have accurate data on the COMPGLAS™ material thermal expansion coefficient, tensile strength and strain to failure, elastic modulus, compression strength and strain to failure, and Poisson's ratio, all as a function of composite orientation. While certain properties such as flexural strength and thermal expansion coefficient have been previously determined for the chopped graphite fiber/7740 borosilicate glass system, the tensile and compression properties have either been just cursorily determined or not

measured at all. Therefore, the following section covers the determination of the composite mechanical properties that were deemed necessary for an accurate design study on the use of this particular COMPGLAS^{TM} material as a gun barrel liner to be undertaken.

DISCONTINUOUS GRAPHITE FIBER/BOROSILICATE GLASS COMPOSITE MECHANICAL PROPERTIES

Discontinuous graphite fiber reinforced glass matrix composites have been developed previously at UTRC as part of a Corporate sponsored research program (Ref. 7). In this work it was demonstrated that the use of a two-dimensional array of discontinuous graphite fibers obtained from the International Paper Co., Tuxedo Park, NY could be used to reinforce a borosilicate glass (Corning Glass Works 7740) to achieve high strength and fracture toughness. The overall data obtained, however, was inadequate for the design of the previously discussed gun barrel liners. In particular, tensile stress-strain data in the "3" direction, Fig. 2, and compression data in all directions were lacking. To overcome this deficit a series of mechanical tests were performed. Reference to the coordinate axes of Fig. 2 will be used in the following discussion.

Composite Tensile Properties in the 1-2 Plane

Through control of the composite lay-up and fabrication procedures it is possible to achieve a very nearly "in plane" isotropy of mechanical performance. Thus, composite properties in plane were measured in only a single direction through the use of tensile specimens measuring 10 cm (4 in.) long, 0.5 cm (0.2 in.) wide and 0.22 cm (0.09 in.) thick. Each specimen, Fig. 3a, retained a 2.5 cm (1 in.) long gauge length and had fiberglass doublers epoxied to each end for the purpose of gripping. Two 0/90 strain gage pairs, one pair on each specimen surface, were bonded to each specimen and used to measure axial and transverse (Poisson) strain.

A typical axial (parallel to the direction of stress application) stress vs. strain curve obtained is shown in Fig. 4, where it can be seen that composite behavior is very different from that of traditional ceramic materials. The tensile stress-strain behavior is initially very linear with a well defined elastic modulus of 54.5 GPa (7.9 Msi). At a tensile stress of 85 MPa (12.3 ksi) the curve shape changes drastically with a major decrease in slope followed by a later increase in stress with increasing strain. The nonlinear behavior can be associated with the onset of matrix microcracking which continues until ultimate composite failure occurs at a stress of 141 MPa (20.5 ksi). This phenomenon has been explored previously at UTRC; and it was shown that as a result of microcracking, the elastic modulus of the composite on subsequent unloading-loading cycles was decreased. This is probably an important point for the gun barrel liner application where the composite liner will see multiple loading cycles. If these cycles apply tensile stresses greater than those at the "knee" of the stress-strain curve, there will have to be some allowance for the change in elastic modulus. Because of the

importance of this point a proportional limit stress, corresponding to the approximate initial deviation from linearity, is also reported in the overall data, Table I.

Composite transverse Poisson contraction strain is shown as a function of applied stress in Fig. 5. The general shape of this curve is quite similar to that shown in Fig. 4, although the magnitude of strain is much smaller. Using the strain in the initial linear portion of this curve, it was possible to calculate a Poisson's ratio μ_{12} of 0.18.

A total of three tensile specimens were tested. In each case composite fracture occurred at the edge of the fiberglass doublers indicating that there may have been some stress concentration effect at this location.

Composite Tensile Properties in the 3 Direction

Composite properties in the "through thickness" or 3 direction were achieved by tensile testing 1.1 cm (0.43 in.) diameter right circular rods of composite that were core drilled out of a 2.4 cm (0.95 in.) thick block of composite material. The specimens were epoxied into threaded steel end fittings leaving a 1.5 cm (0.6 in.) long gage section which was strain gaged to measure specimen axial strain on opposing specimen sides. The specimen geometry is shown in Fig. 3b.

A typical tensile stress strain curve is shown in Fig. 6 indicating that, unlike the previous example, the curve is completely linear up to the point of fracture. In addition, the levels of strength, elastic modulus and failure strain are lower than those for the 1-2 plane due to the fact that no fibers are parallel to the 3 direction. All of the specimens failed within their gage sections and the complete data are presented in Table I.

Three-Point Flexure Testing

Two specimens were tested in three point flexure in the 1 direction just to provide a comparison with previous data obtained for specimens fabricated in the past at UTRC. The specimen dimensions are 10 cm (4 in.) long, 0.5 cm (0.2 in.) wide, 0.23 cm (0.09 in.) thick, and were tested using a span of 6.4 cm (2.5 in.). A typical load vs. specimen mid span deflection curve, Fig. 7, again indicates the nonlinear behavior of the composite. It is interesting to note that the stress at which departure from linearity occurs is in close agreement with the stress at which this departure occurred in the tensile test, Fig. 4. This is to be expected since the major difference between 3 point bend and tensile behavior is expected due to subsequent composite non-linear behavior. Thus, the calculated maximum flexural stress at composite

fracture in Fig. 7 is substantially greater than the composite tensile strength. This is due to the inability of the elastic flexural stress calculation to deal with nonlinear material behavior through the beam section. The flexural elastic modulus, on the other hand, is in relatively good agreement with the tensile test determined value because it is taken prior to the onset of matrix microcracking. Composite data are summarized in Table I.

Composite Compression Properties in the 1-2 Plane

Composite compression stress-strain data were obtained through the end loading of flat plates of material that were 0.25 cm (0.1 in.) thick, 7.9 cm (3.1 in.) long and were either parallel sided or dog-boned in shape. The specimens were side supported over a length of 7.3 cm (2.9 in.) to prevent Euler buckling and were strain gaged on both sides to provide axial and Poisson strain measurement. Several test iterations indicated that the specimen dog-bone shape was required to avoid a specimen end brooming failure mode, Table II. The final specimen configuration used to determine composite compression strength is shown in Fig. 3c and a typical stress-strain curve is shown in Fig. 8. The overall curve is primarily linear with an initial nonlinear portion that remains unexplained. The slope of the large linear segment of the overall curve was used to determine composite elastic modulus and was found to provide a value in good agreement with that obtained from tension testing. The data obtained from these tests is summarized in Table II, where it can be seen that (when end brooming was eliminated) the specimens failed at a stress much higher than the composite tensile strength and very near to the three-point flexural strength. The "dog bone" specimen failures occurred in the gage section of the specimens at locations near the radii of the specimen ends. Fracture appeared to occur on an angle through the specimen thickness giving the appearance of a compression induced shear failure.

The values of composite Poisson's ratio, taken from the linear segment of the stress-strain curve used for elastic modulus, also agree well with the values determined in tension.

Composite Compression Properties in the 3 Direction

Compression testing was performed on right circular rods of composite equal in size to those used for tensile testing in this same orientation, Fig. 3d. These specimens were also strain gaged and, because of their large diameter and relatively short length, were not side supported during testing. A typical compression stress-strain curve is shown in Fig. 9 where it can be

seen that the curve is linear to the point of failure. The elastic modulus taken from this curve agrees well with that obtained from tensile testing; however, the compression strength is much higher than the tensile strength. Unfortunately, the strain gages applied to all three compression specimens debonded after approximately 0.5% strain and deflectometer readings were required to measure the remaining curve shape so there is some uncertainty in the strain behavior above this value. Thus, the ultimate failure strains, Table III, are given as being in excess of 2% rather than a precise number.

Of the three specimens tested, one failed at a lower stress value by a small chip breaking loose at one of the specimen ends. Although this specimen could have been loaded to still higher stress levels the test was stopped at that point. In contrast, the other two specimens failed by multiple fracture throughout the entire specimen at the much higher stress level.

FABRICATION TECHNIQUES

Hot Isostatic Pressing (HIP)

The use of HIP was considered for the fabrication of gun barrel liners in which the fibers are all located in circumferential wraps. In this design the highest composite strengths would be in the axial and tangential cylinder directions while the weakest orientation would be in the radial direction. A variety of procedures were used in an attempt to determine the best composite preform type and HIP container material to be used. The following describes the procedures used.

<u>Composite Preform Preparation</u> - In all cases the 2-D discontinuous graphite fiber paper (International Paper Co., Tuxedo Park, NY) was used as the reinforcement. It was prepared in the standard manner of dipping into a slurry of borosilicate glass in propanol and then dried. In the case of cylinder fabrication, a long strip of paper was continuously pulled through the slurry and then wrapped onto a mandrel of the desired diameter. The mandrel was prewrapped with molybdenum foil to provide a bond release agent. After this, the preform was air dried to remove the propanol and then heat treated in vacuum to remove any excess volatiles and also to remove the organic binder which is originally supplied on the discontinuous fiber paper. A maximum heat treatment temperature of 1200°C (2190°F) was chosen to assure that no additional volatiles would be present during the final HIP run since internal gas evolution could cause HIP container failure. After heat treatment the preform was placed in the appropriate HIP container which was then once again baked out under vacuum, this time at only 300°C (575°F), to drive off any moisture introduced from the lab, air or encapsulation procedure. Final vacuum sealing of the HIP container then took place.

After final sealing, the container was placed in the HIP and subjected to the following cycle:

- Heat to 815°C (1500°F) in 1 hr
- Hold for 10 additional minutes
- Apply 1500 psi pressure
- Heat to 1205°C (2200°F) in 1 hr
- Hold at temperature for 10-30 minutes
- Cool and remove from HIP.

Both glass and metal HIP containers of various geometries were used as described below.

Glass HIP Container - Borosilicate glass HIP containers have been used extensively at UTRC in the past to densify powder metallurgical superalloys. In this case the glass has served at high temperatures as a sealant to the surface of the part to be densified. Because the matrix of the herein discussed composite is also a borosilicate glass it was thought that this type of HIP container would be ideal. In all attempts, however, the borosilicate glass did not effectively seal off the HIP gas medium and the resultant composite remained undensified. Three different HIP geometries were tried, Fig. 10, and in each case the results were unsatisfactory. A flat plate, Fig. 10a, HIP forming around a solid central core, Fig. 10b, and internal expansion forming to the inner surface of a solid alumina cylinder, Fig. 10c, all were unsuccessful because the glass envelopes failed to completely seal the composite from the HIP gas environment.

Metal HIP Containers - The use of a stainless steel metal envelope is another approach to creating a container which will provide an adequate seal to the HIP atmosphere. In this case it was possible to demonstrate that the envelope integrity could be maintained throughout the HIP operation; however, the "debulking" characteristics of the composite lay-up prevented the development of a desired shape. The two basic concepts tried are shown in Fig. 11. These included both the forming of a cylinder around a solid core and also the use of a hollow center to expand the cylinder outward. In this latter case the procedure was tried with a thinner inner tube wall thickness as well as equal inner-outer tube wall thicknesses.

The composite microstructures shown in Fig. 12 were obtained by HIP with the use of the steel outer tube and solid carbon inner core. Carbon was used as a core because it could be easily machined out after densification. Al though there was some residual porosity, the composite was relatively well densified. Unfortunately, the large level of debulking which took place caused the composite to end up in a noncylindrical shape. This also proved to be the major problem with the hollow center tube technique. As in the case of the solid core, composite densification could be achieved, and in this case the central core remained relatively cylindrical. However, the outer circumference included two extensions, Fig. 13, which occurred due to folding of the wrapped composite during densification. These occurred due to the extensive change in ply thickness (greater than a factor of four) that occurs during densification. When occurring by circumferential compression of the tube, the plies buckle and distort as shown. Thus it was thought best to use a thinner inner steel tube and a thicker outer tube to achieve densification by inner expansion of the composite. This, however, was unsuccessful in an attempted trial run, due to rupture of the inner tube wall.

Since it had been decided, as detailed in the following section, that the best fiber orientation would be one in which the fibers were all oriented in the radial and circumferential directions (none in the axial tube direction), further experiments were not performed and the remaining cylinder fabrication work was performed primarily by hot pressing. The one exception was the attempt to creep form cylindrical sections described below.

Creep Forming Predensified Plates

A second original design concept was the use of a segmented cylinder liner, as was shown in Fig. 1. This concept was not pursued fully since, as was mentioned previously, the stress analysis performed by Maremont Corp. indicated that the fiber orientation in this concept was not desirable; however, one segment of a cylinder was successfully fabricated by creep forming. It was decided to form one third segments of a cylinder in a shaped die, as shown in Fig. 14. Preconsolidated plates of randomly oriented chopped graphite fiber/7740 borosilicate glass of dimensions 2" x 4" x 0.350" could then be creep formed into one-third cylinder segments of 0.200 inner radius and 0.550 outer radius and 4" long with sufficient material remaining for the attachment area between the three cylindrical segments.

One creep forming experiment was run by pressing a plate of graphite/borosilicate glass at 1200°C in the shaped dies of Fig. 14. A pressure of 1000 psi was used to creep form the plate into the desired shape. Ram motion was monitored such that when all motion ceased the pressure was removed and the pressed piece allowed to cool. On examination after pressing, it was found that the sample had conformed to the die shape very well (Fig. 15) except that the cylindrical segment thickness along its axial mid point was somewhat less than the desired 0.350". This problem could undoubtedly be solved by either pressing to preadjusted stops or by using less than 1000 psi pressure during the creep forming step.

While this concept was not pursued due to the aforementioned reasons, the one experiment performed indicated that creep forming the graphite/glass material in shaped dies is a feasible method of producing certain types of component configurations to near net shape dimensions.

Hot Pressing

Uniaxial hot-pressing of graphite/glass composites was employed to produce composite cylinders with fiber orientation as was shown in Fig. 1 for concept #3. In this concept, all fibers are in the radial and tangential directions only, with no fibers in the direction along the axis of the cylinder. As will be explained in the next section, this fiber alignment was

selected as the most viable for withstanding the expected stresses generated during gun barrel assembly and testing.

The procedure used to fabricate composite cylinders by this method consisted of hot-pressing a billet of material and then diamond core drilling the cylinders out of this billet. The 3" x 3" x 4" high billet was fabricated by the standard method of dipping 3" squares of 2-d discontinuous graphite paper into a slurry of borosilicate glass powder (-325 mesh) in propanol. After drying, the glass powder impregnated tapes were laid up in a graphite mold, baked out at 400°C to remove the binder on the graphite paper, and then hot-pressed at 1200°C for 15 min in 10^{-5} torr vacuum. Approximately 0.500" thick plates were produced by this method. Larger thicknesses could not be produced in the available dies due to the large amount of debulking required to compact the stack of graphite paper tapes into a fully dense plate. Thus, eight plates of ~0.500" thickness were pressed individually and then repressed together to form the final 3" x 3" x 4" thick block of graphite/glass composite material. Past work had shown that no discontinuities are introduced at the bond line between plates when this method is used.

Four 4" long cylinders were diamond core drilled from the hot-pressed block of material. The cylinders produced by this method had nominal ID's of 0.475" and OD's of 0.925", and are shown in Fig. 16. One of the cylinders was drilled incorrectly resulting in one end having a slightly off center ID and OD. Fortunately, only three cylinders are required for the test firing procedure. These cylinders were then sent to Maremont Corp. for final machining and assembly into metal sleeves prior to the test firing. The following two sections of this report, written by Maremont Corp., discuss the analytical work, assembly, and test firing as performed by Maremont Corp.

ANALYSIS OF BOROSILICATE GLASS/GRAPHITE FIBER REINFORCED BARREL LINERS

This section summarizes the analytical work performed by Saco Defense Systems Division of Maremont Corp. under contract to United Technologies Research Center (UTRC). The effort was subdivided into three major tasks which are described below.

- A general evaluation of the structurally important material properties and their influence upon the design parameters which must be employed to achieve a structurally sound liner installation. This evaluation would also uncover inherent material shortcomings which must be addressed through a revision of material properties or possibly through alternate design concepts.

- Selection of liner geometry and interference fits for three test barrels to be used in verification tests. Only ambient barrel temperatures were considered in this analysis.

- Parametric study to evaluate the effects of variable liner wall thickness and modulus of elasticity on the maximum liner stresses caused by bore pressure. These data give the material designer insight into the mutual interdependence of these two variables and can be a useful guide in the evaluation of alternate materials.

Evaluation of Material Properties

The properties of the UTRC borosilicate/graphite fiber reinforced material are significantly different from those of silicon carbide liners which had been previously developed and successfully test fired by Saco Defense Systems Division under U.S. Government contract (Ref. 1).

The significant differences from a structural standpoint are as follows:

- Tensile and compressive strength properties as well as the modulus of elasticity depend on the orientation of the reinforcing fibers. In the material supplied, with planar fiber orientation, material properties are equal in two directions only (Principal Axis 1 and 2) while tensile strength in the third direction (Principal Axis 3) is very limited.

  It was decided to orient principal axis three in the axial direction of the liner for the following reasons:

  1. The low magnitude of axial liner stresses.

2. To maintain identical strength and elastic properties in the plane of the two principal liner stresses, radial and tangential.
3. Liners of this orientation could most easily be fabricated by UTRC.

- Material strength, especially in compression, is very low when compared to high strength ceramics.

- The modulus of elasticity of the liner material is considerably lower than that of the surrounding steel barrel (8 Msi vs 30 Msi). In contrast, previously investigated ceramics exhibit a modulus of elasticity significantly higher than that of steel.

- The thermal coefficient of expansion is much less than that of steel (approximately 15%).

A comparison of the graphite/glass material properties with those of steel and silicon carbide are shown in Table IV.

In order to evaluate the structural properties of the material, calculations were performed on a liner installation in the barrel configuration of the M2 heavy barrel machine gun (.50 cal.).

Results - The results are shown in Table V and Figs. 17 and 18. Table V shows the radial and tangential stresses of the graphite/glass liners at various wall thicknesses and interference fits. Stresses caused by bore pressure only and by shrinkfit (if any) are listed separately. The resultant stresses are those that the liner "sees" under firing condition.

Figure 17 shows the tangential and radial wall stresses and stress gradients throughout the liner wall under conditions of maximum bore pressure as a function of liner wall thickness.

Figure 18 indicates the loss of shrinkfit (or gap between liner and sleeve if no shrinkfit is employed) as a function of barrel temperature. Barrel temperature is assumed to be stabilized, i.e. there is no temperature gradient across the entire wall section, including the liner. Also shown are the tangential and radial shrink stresses in the liner versus barrel interference fit.

Note: The material properties evaluated are those in the plane of the reinforcing fibers (Principal Axis 1 and 2), material properties along principal axis 3 were not considered. The modulus of elasticity (E) and Poisson's ratio (V) used in these calculations were 7.5 Msi and .15 respectively, based on preliminary information. A later revision of these values to 8.0 Msi and .19 has an insignificant effect on the results obtained.

Conclusions - Although based on the results of calculations for a specific caliber, the conclusions drawn remain valid for geometrically scaled barrel configurations, assuming no change in material properties.

- Because the modulus of elasticity of the liner material is considerably lower than that of the barrel itself (8 Msi vs 30 Msi) the bore pressure loads are largely reacted by the barrel and liner stresses remain at relatively low levels. Thus, lower material strength properties become acceptable if accompanied by a sufficiently low modulus of elasticity.

- The tangential (tensile) liner stresses due to bore pressure decrease significantly as the liner wall thickness is reduced. The radial (compressive) stresses, however, are not significantly affected by decreasing liner wall thickness. It is, therefore, concluded that the lowest practical liner wall thickness should be selected.

- Radial compressive stresses at the bore surface are numerically equal to the bore pressure (approx. 55,000 psi max.). The liner material must be capable of handling this stress level.

- The pressure stresses are dynamic in nature. The duration of the calculated peak stress level is measured in fractions of a millisecond. Direct comparison of these data with the static strength properties of the liner material is, therefore, misleading since material properties tend to be considerably higher under dynamic conditions. Until information on the dynamic strength and fatigue properties of ceramic liner materials becomes available, the computed data can only serve as a guideline.

- Pressure stresses in the liner wall are not uniform but subjected to substantial gradients. It is suggested, therefore, that the modulus of rupture (flexural strength), or some modification thereof, is perhaps a more valid criterion for the evaluation of liner tensile capability than the direct tensile strength.

- The low coefficient of thermal expansion of this material results in rapid loss of shrinkfit at elevated (stabilized) barrel temperatures. In order to maintain at least wall to wall contact between liner and barrel at realistic maximum barrel temperatures (assumed at 1200°F), shrinkfits would have to be employed which would result in compressive stresses exceeding the yield strength of the material. Without such shrinkfits, a gap would form between liner and barrel which would, presumably, result in immediate tensile liner failure under bore pressure conditions.

Selection of Liner Geometry and Interference Fits for Three Test Barrels

Additional computations were performed to "fine tune" the interference fits which would result in reasonable conformance of the computed stress levels with the known static strength properties of the material. Liner wall thickness was established at .200 in. and .150 in. with .150 in. thought to be the minimum practical thickness, at least during the initial fabrication, to insure liner integrity during handling and installation.

The configuration of the test barrel is the same that was used in previous liner tests on silicon carbide, namely, the liner is first installed into a metal sleeve of gun barrel material which in turn is interference fitted into the jacket or barrel proper (Fig. 19). In view of the low interference fits required, the separate sleeve is theoretically not necessary, but was retained because it facilitates liner installation. The results of the computer runs are shown in Table VI (refer to Fig. 20 for stress location).

The configurations selected for hardware fabrication were as follows:

Configuration	Comp. Run	Liner Wall (in.)	Diametral Interference Liner/Sleeve (in.)	Diametral Interference Sleeve/Jacket (in.)	Tensile Stress Max. (ksi)	Tangential Stress Range (ksi)
1	1	.200	.0005	.0005	32.2	40.3
2	2	.200	.0015	.0005	20.7	41.1
3**	8**	.150	.0015	.001	12.2	35.4
3	9	.150	.0015	.0017	9.1	35.3

**This was the original selection. However, due to a drawing error, the actual interference conditions between liner and sleeve were .0017 in. instead of .001 in. as originally planned. Thus, the actual test hardware is represented by the results of computer run #9.

The configurations were chosen on the basis of the resultant tensile (tangential) stress. Configuration 1 has a stress exceeding the material ultimate (static) limit. Configuration 2 has a stress approximately at this limit, while the stress in configuration 3 is below this limit.

Parametric Study

The results of a parametric study to evaluate the effects of variable liner thickness and elastic modulus on the stresses caused by bore pressure are presented in Figs. 21 and 22. The results are in agreement with the conclusions previously stated.

GRAPHITE/GLASS COMPOSITE BARREL ASSEMBLY AND FIRING TEST RESULTS

Barrel Assembly

Three barrel assemblies consisting of a liner, sleeve, jacket, muzzle section, and nut were manufactured at Saco Defense Systems Division of Maremont Corp. to obtain the diameters and interference fits previously selected. The manufacturing sequence was as follows:

1. Finish grind liner all over and hone sleeve to obtain desired interference.
2. Heat sleeve and assemble with liner.
3. Grind sleeve OD to size and concentric with liner ID.
4. Hone jacket ID to obtain desired interference fit.
5. Heat jacket and assemble with liner/sleeve subassembly.
6. Assemble with muzzle section and tighten nut.

The actual diameters and interference fits obtained on the various components are summarized in Table VII. The actual results achieved were very close to the desired target values.

The change in liner ID resulting from shrink fitting into sleeves and jackets is summarized in Table VIII.

After assembly, each liner was inspected for ID size, surface finish, and evidence of cracks using fluorescent penetrant inspection techniques. All assemblies were observed to have circumferential indications of cracks in the bore approximately 1/4 to 3/4" from the muzzle end of the liner. These cracks were observed after the liner was assembled into the sleeve and jacket. It is not known whether indications were present after assembly into the sleeve only since no inspection was performed at this level. However, it is highly probable that the indications observed are associated with the assembly of the liner/ sleeve subassembly into the jacket since all observed indications were located on the muzzle end of the lined assembly. This would be highly unlikely if the cracks were initiated at the subassembly level. A tendency to crack in this same area was observed previously on alpha silicon carbide liners of the same configuration. This may be connected, at least in part, with the nonuniformity of the heating or cooling of the jacket when shrink fitting the liner/sleeve subassembly. The heating method to be used for future assemblies will be modified to obtain more uniform heating and cooling.

Firing Tests

Each barrel assembly was fired by remote control for a total of 10 shots single fire. The liner bore surface was examined visually with a bore scope after the first and third round, after the sixth round, and again after the tenth round. As a safety precaution, the bore was visually inspected after each round for the presence of any obstructions which may have resulted from catastrophic liner failure. Figure 23 shows assembly #3 after the firing tests. Liner bore diameters were measured at 1" intervals before and after firing and the results are shown in Fig. 24. The change in bore diameter varies from .0000 to .0002".

The liner ID surface finish was also measured before and after firing and the results are summarized in Table IX. A noticeable increase in surface roughness was observed. One very encouraging result was that although all assemblies showed indications of cracks after assembly, these cracks had no tendency to grow during firing. In fact, on assembly #3, the indication visible before firing could not be found again after firing. Possibly this was a very shallow crack which was polished out by the firing or the crack which was present was filled with debris and was, therefore, closed to the penetrant.

On assembly #2, the indication observed before firing appeared unchanged after ten rounds.

Assembly #1 was faced back approximately 1/2" to remove the circumferential crack indication. This assembly was reinspected and found to be free of indications prior to firing. After firing 10 rounds, there were no indications visible on the bore. Two indications were visible on the muzzle face, however, but these had no apparent depth and appeared to be scratches rather than cracks. The results of penetrant inspection on the various assemblies are summarized in Table X.

In summary, the test results seem to indicate that the use of a low modulus composite ceramic material as represented by graphite fiber reinforced borosilicate glass has considerable potential. The material is capable of withstanding the pressure stresses resulting from firing without failure. Even when pre-existing cracks are present, the material exhibits no tendency for crack growth or catastrophic failure. Measurements of liner bore diameters before and after firing indicate a tendency for the bore to increase by .0001 to .0002".

CONCLUSIONS AND RECOMMENDATIONS

It can be concluded from the results of this program that the use of a lightweight, low modulus fiber reinforced glass matrix composite with high toughness as a liner for gun barrel applications is feasible. More specifically, it was demonstrated that a discontinuous graphite fiber reinforced borosilicate glass matrix composite liner could withstand the pressure stresses generated during 10 round single shot firing of a .50 caliber projectile without failure and with minimal increase in bore diameter. This was demonstrated for three configurations of liner geometry and interference fit that resulted in tangential tensile stresses that were less than, equal to, and actually in excess of the material ultimate tensile strength.

While the fabrication methods of hot isostatic pressing (HIP) and creep forming of cylinders that were investigated under this program did not result in the successful fabrication of cylinders nor the optimum configuration of fiber reinforcement for this particular application, variations upon these fabrication methods could ultimately prove useful for the fabrication of cylinders with some fiber reinforcement in the axial direction. While stresses in this direction are not significant during firing, they can arise during the shrink fitting procedures, as evidenced by the circumferential cracks found in all three assemblies near the muzzle end of the liner. While more uniform heating and cooling of the jacket when shrink fitting the liner/sleeve subassembly may alleviate this problem, the presence of fibers in the axial direction would certainly be desirable.

From the results of 10 rounds of single shot firing, it would seem justified to perform additional single shot testing to evaluate the resistance of the liner to erosion and wear. If the results of this testing are favorable, the liners should be evaluated under automatic firing conditions that more closely approach the actual environment of the gun. Automatic firing conditions will impose upon the liner the added condition of operating at elevated temperature. This could pose a problem for the graphite fiber/borosilicate glass composite system, as discussed in the introduction, and may necessitate the use of a higher temperature COMPGLAS™ system such as SiC fiber reinforced lithium aluminosilicate (LAS) glass-ceramic.

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Table I

Tension Test Data

Orientation	Proportional Limit		Elastic Modulus		Tensile Strength		Failure Strain	Poisson's Ratio
	MPa	(ksi)	GPa	(Msi)	MPa	(ksi)	%	μ_{12}
1	57.9	(8.4)	56.5	(8.20)	134	(19.4)	0.76	0.19
1	83.4	(12.1)	54.5	(7.91)	141	(20.5)	0.88	0.19
1	77.2	(11.3)	57.2	(8.29)	126	(18.3)	0.72	0.19
Avg.	73.0	(10.6)	55.8	(8.10)	134	(19.4)	0.79	0.19
3	-		37.6	(5.46)	9.0	(1.3)	0.02	-
3	-		35.1	(5.09)	6.5	(0.9)	0.02	-
3	-		34.8	(5.05)	6.3	(0.9)	0.02	-
Avg.			35.8	(5.2)	6.9	(1.0)	0.02	-

Flexural Test Data

Orientation	Proportional Limit		Elastic Modulus		Flexural Strength	
	MPa	(ksi)	GPa	(Msi)	MPa	(ksi)
1	79.8	(11.6)	51.3	(7.44)	297	(43.1)
1	95.8	(13.9)	55.4	(8.03)	327	(47.5)

Table II

Compression Test Data for Specimens in the 1-2 Plane
(Side Supported Specimens)

Specimen Type	Failure Mode	Elastic Modulus GPa	Elastic Modulus (Msi)	Failure Stress MPa	Failure Stress (ksi)	Failure Strain %	Poisson's Ratio μ_{12}
"Dog Bone"	Compression-Shear	53.8	(7.80)	308	(44.7)	0.55	-
"	"	54.8	(7.95)	354	(51.3)	0.55	-
"	"	53.6	(7.77)	298	(43.2)	0.54	-
	Avg.	54.4	(7.9)	319	(46.4)	0.55	
Parallel Sided	End Brooming	52.2	(7.57)	211	(30.6)		-
"Dog Bone"*	"	52.7	(7.65)	274	(39.8)		0.19
Parallel Sided	"	51.4	(7.46)	194	(28.2)		0.19

*This dog bone specimen had a gage section width of 1.4 cm (0.55 in.) rather than the 0.6 cm (0.24 in.) standard.

Table III

Compression Test Data for Specimens
Tested in the 3 Direction

Failure Mode		Elastic Modulus GPa	(Msi)	Failure Stress MPa	(ksi)	Failure Strain %
Multiple Fracture		38.7	(5.62)	781	(113)	≥2
Single Chip		36.3	(5.27)	442	(64.1)	≥2
Multiple Fracture		36.7	(5.32)	781	(113)	≥2
	Avg.	37.2	(5.4)	778	(113)*	≥2

*Chipped specimen data not included in average

Table IV

Comparative Properties of Liner and Barrel Materials
at Ambient Temperature Conditions Except as Noted

	Graphite/Glass Composite	Sintered Alpha Silicon Carbide (at 1472°F)	Cr, Mo, V Gun Steel
Thermal Conductivity BTU-in./Hr-°F-ft^2 (C)	Unk.	343.0	324
Modulus of Rupture (psi) (R)	45,300	64,100	
Young's Modulus (psi) (E)	8×10^6	59.4×10^6	30×10^6
Coef. of Thermal Expansion (1/°F) (A)	$.94 \times 10^{-6}$	2.67×10^{-6}	6.3×10^{-6}
Poisson's Ratio	.19	0.142	0.30
Ult. Tensile Strength (psi)	19,400	48,000	200,000
Compressive Strength (psi)	46,400	500,000	200,000

Table V

Material Property Evaluation
Summary of Computer Runs

Bore Dia. - .51 in.
Barrel OD - 1.93 in.
Mono-block Barrel - no separate sleeve
Poisson's Ratio - .15 except as noted

Run #	E_L x 10^{-6}	t Wall Thickness of Liner (in.)	Liner OD (in.)	Interf. at Liner (in.)	Radial Stresses (ksi)* 1	1'	Tangential Stresses (ksi)* 1	1'	2	2'
1	7.5	.20	.91	.004	-55	-22.5	39.6	7.2	35.4	12.8
					0 / -55	-14.8 / -37.3	-43.0 / - 3.4	-28.2 / -21.0	23.2 / 58.6	8.4 / 21.2
2	7.5	.20	.91	0	-55	-22.5	39.6	7.2	35.4	12.8
3	7.5	.10	.71	0	-55	-34.6	29.1	8.7	45.4	10.8
4	7.5	.06	.63	0	-55	-41.5	23.2	9.7	51.4	9.9
5	5.9	.10	.71	0	-55	-35.5	25.4	5.9	46.7	11.1
6	5.9	.20	.91	0	-55	-23.6	36.5	5.1	37.1	13.5
7	5.9	.20	.91 (μ = .3)	0	-55	-25.3	31.3	1.79	39.9	14.5
8	7.5	.20	.91	.002	-55	-22.5	39.6	7.2	35.4	12.8
					0 / -55	- 7.4 / -29.9	-21.5 / +18.1	-14.1 / - 6.9	11.6 / 47.0	4.2 / 17.0
9	7.5	.20	.91	.001	-55	-22.5	39.6	7.2	35.4	12.8
					0 / -55	- 3.7 / -26.2	-10.6 / +29.0	- 7.1 / .1	5.8 / 41.2	2.1 / 14.9

*See Fig. 20 for stress locations

Table VI

Liner Selection for Test Hardware

Run #	E_L x 10^{-6}	t Liner (in.)	OD Liner (in.)	Int. Liner (in.)	Int. Jacket (in.)	Type Stress	Radial Stresses (ksi) 1	1'	2	2'	3	3'	Tangential Stresses (ksi) 1	1'	2	2'	3	3'
1	8	.200	.91	.0005	.0005	P	-55	-22.3	→	- 6.4	→	0	40.3	7.6	37.6	21.7	21.7	15.3
		Configuration #1				S	0	- 2.8	→	- 2.6	→	0	-8.1	-5.3	-2.2	-2.4	8.9	6.3
						R	-55	-25.1	→	- 9.0	→	0	32.2	2.3	35.4	19.3	30.6	21.6
2	8	.200	.91	.0015	.0005	P	← SAME AS RUN #1 →											
		Configuration #2				S	0	- 6.7	→	- 3.7	→	0	-19.4	-12.8	4.4	1.4	12.7	9.0
						R	-55	-29.0	→	-10.1	→	0	20.7	- 5.2	42.0	23.1	34.4	24.3
3	8	.200	.91	.0005	.001	P	← SAME AS RUN #1 →											
						S	0	- 3.6	→	- 4.7	→	0	-10.4	- 6.9	-7.7	-6.6	15.9	11.3
						R	-55	-25.9	→	-11.1	→	0	29.9	.7	29.9	15.1	37.6	26.6
4	8	.200	.91	.0015	.001	P	← SAME AS RUN #1 →											
						S	0	- 7.5	→	- 5.8	→	0	-21.8	-14.3	-1.2	-2.8	19.7	13.9
						R	-55	-29.8	→	-12.2	→	0	18.5	- 6.7	36.4	18.9	41.4	29.2
5	8	.150	.81	.0005	.0005	P	-55	-27.7	→	- 5.9	→	0	35.4	8.1	41.8	19.9	19.9	14.1
						S	0	- 2.6	→	- 2.6	→	0	- 8.5	- 5.9	-2.6	-2.6	8.7	6.1
						R	-55	-30.3	→	- 8.5	→	-	26.9	2.2	39.2	17.3	28.6	20.2
6	8	.150	.81	.0015	.0005	P	← SAME AS RUN #5 →											
						S	0	- 6.3	→	- 3.4	→	0	-21.0	-14.7	3.1	.2	11.4	8.1
						R	-55	-34	→	- 9.3	→	0	14.4	- 6.6	44.9	20.1	31.3	22.2
7	8	.150	.81	.0005	.001	P	← SAME AS RUN #5 →											
						S	0	- 3.2	→	- 4.7	→	0	-10.6	- 7.4	-8.0	-6.5	16.1	11.3
						R	-55	-30.9	→	-10.6	→	0	24.8	.7	33.8	13.4	36	25.4
8	8	.150	.81	.0015	.001	P	← SAME AS RUN #5 →											
						S	0	- 7.0	→	- 5.5	→	0	-23.2	-16.2	-2.3	-3.8	18.8	13.3
						R	-55	-34.7	→	-11.4	→	0	12.2	- 8.1	39.5	16.1	38.7	27.4
9	8	.150	.81	.0015	.0017	P	← SAME AS RUN #5 →											
		Configuration #3				S	0	- 7.9	→	- 8.5	→	0	-26.2	-18.3	-9.9	-9.3	29.1	20.5
						R	-55	-35.6	→	-14.4	→	0	9.1	-10.2	31.9	10.7	49.0	34.6

Table VII

Summary of Dimensional Inspection Results

Liner/Sleeve Dimensions (in.)	Assembly No. 1	2	3
Liner OD	.9100	.9102	.8102
Sleeve ID	.9095	.9086	.8087
Interference (Actual)	.0005	.0016	.0015
Interference (Target)	.0005	.0015	.0015
Sleeve/Jacket Dimensions (in.)			
Sleeve OD	1.3102	1.3126	1.3107
Jacket ID	1.3095	1.3119	1.3090
Interference (Actual)	.0005	.0007	.0017
Interference (Target)	.0005	.0005	.0015

Table VIII

Summary of Liner ID Dimensions and Dimensional Change

	Assembly No.					
	Dia.	Δ	Dia.	Δ	Dia.	Δ
As Received (in.)	.5113		.5122		.5125	
After Shrinking (in.) In Sleeve*	.5111	-.0002	.5113	-.0009	.5119	-.0006
After Shrinking (in.) in Jacket**	.5109	-.0002	.5111	-.0002	.5113	-.0006

*Average of 3 readings
**Average of 4 readings

Table IX

Effect of Firing on Liner ID Surface Finish (RMS)

ID Finish	Assembly # 1	2	3
Before Firing	12	11	12
After Firing	45	20	25

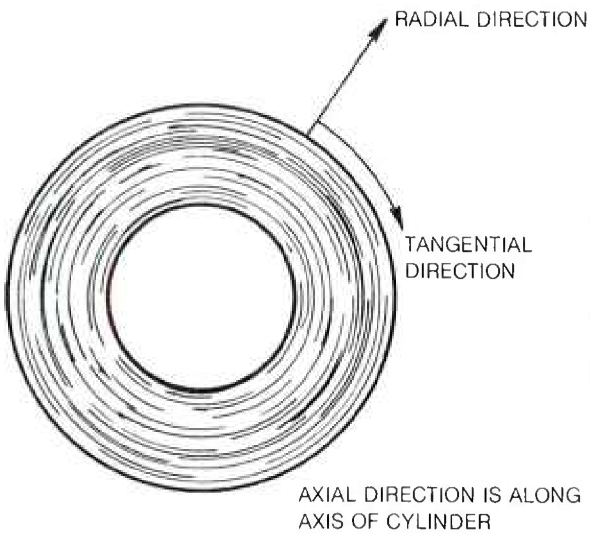
Table X

Summary of Fluorescent Penetrant Inspection

Assembly #	As Assembled	After Rework	After Firing
1	Crack Indication	OK	OK[1]
2	Crack Indication	Not Reworked	Crack Indications Same as Before Firing
3	Crack Indication	Not Reworked	OK[2]

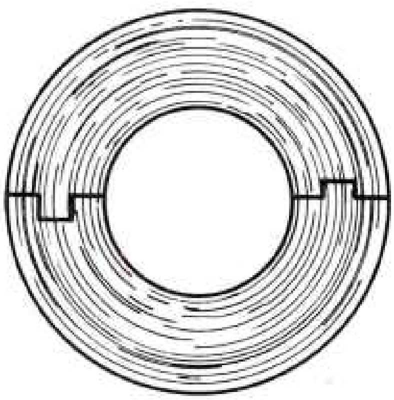
[1] Indications on muzzle end liner face - no apparent depth

[2] Crack indication observed before firing was not visible when inspected after firing



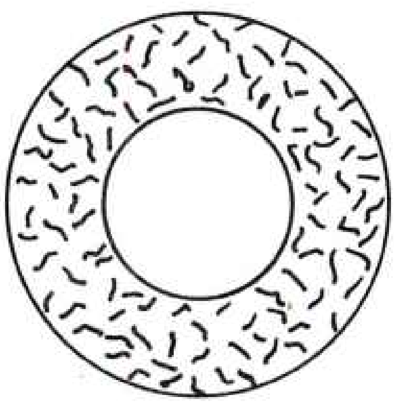
CONCEPT NO. 1

- CIRCUMFERENTIALLY WRAPPED CHOPPED FIBER PLIES
- NO DISCONTINUITIES
- WEAKEST DIRECTION IS RADIAL
- HOT ISOSTATIC PRESSING (HIP) FABRICATION



CONCEPT NO. 2

- CIRCUMFERENTIALLY WRAPPED PLIES
- DISCONTINUITIES FOR EASE OF FABRICATION
- WEAKEST IN RADIAL DIRECTION AND IN TANGENTIAL DIRECTION OF DISCONTINUITIES
- FABRICATION BY CREEP FORMING IN SHAPED DIES



CONCEPT NO. 3

- FIBERS IN RADIAL AND TANGENTIAL DIRECTIONS ONLY
- WEAK IN AXIAL DIRECTION
- FABRICATION BY CORE DRILLING HOT-PRESSED BILLETS

Figure 1 Glass Matrix Composite Cylinder Construction Concepts

81–4–72–9

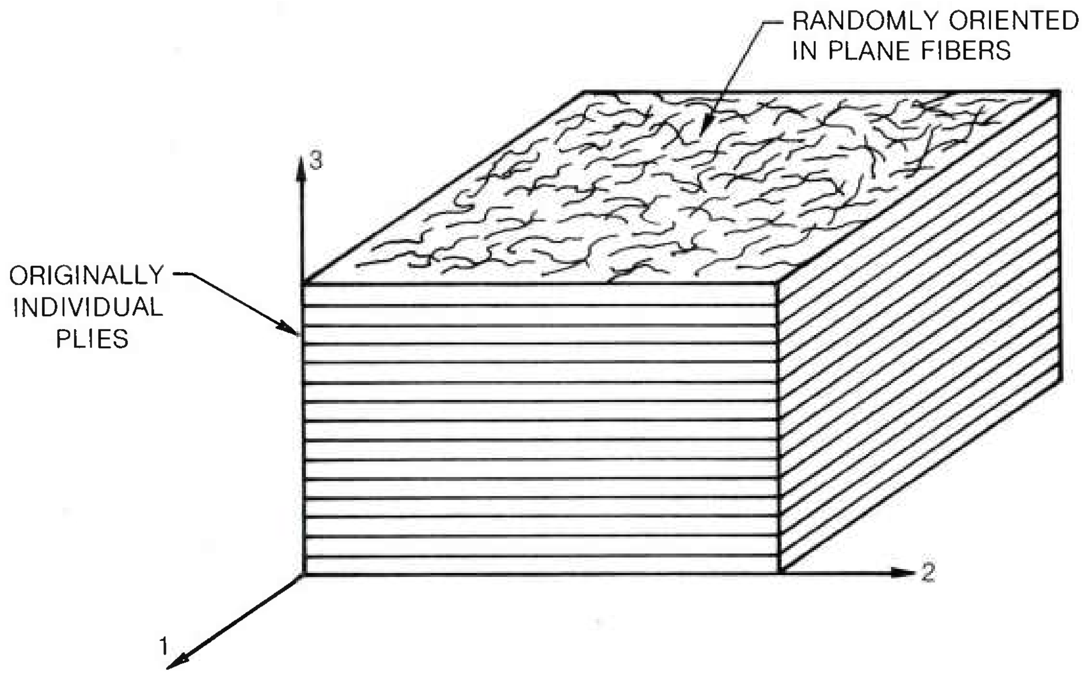
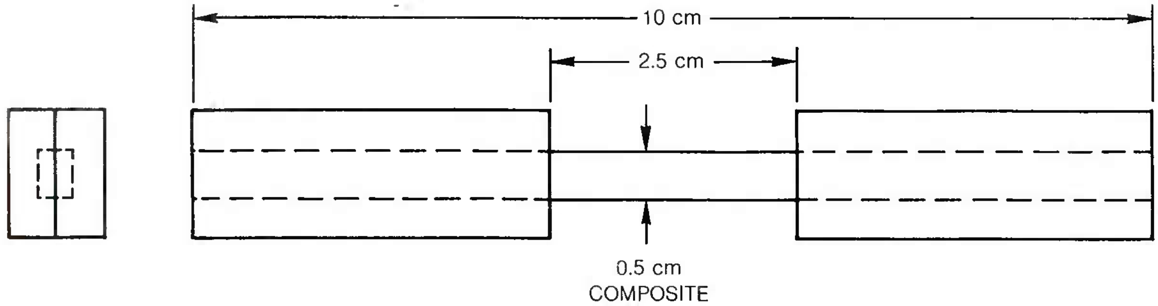
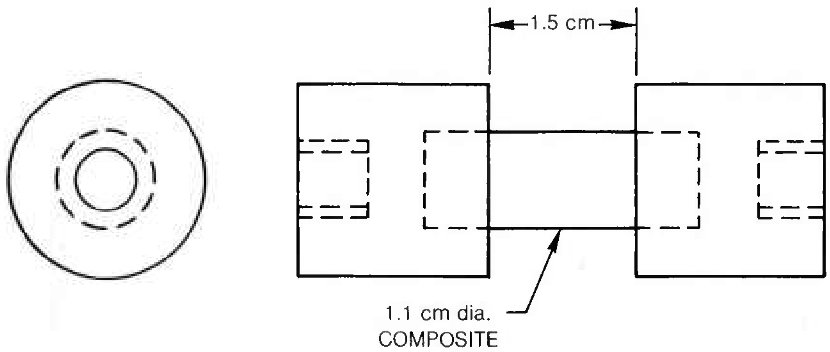


Figure 2 Structure of Graphite Fiber Reinforced Glass Composite

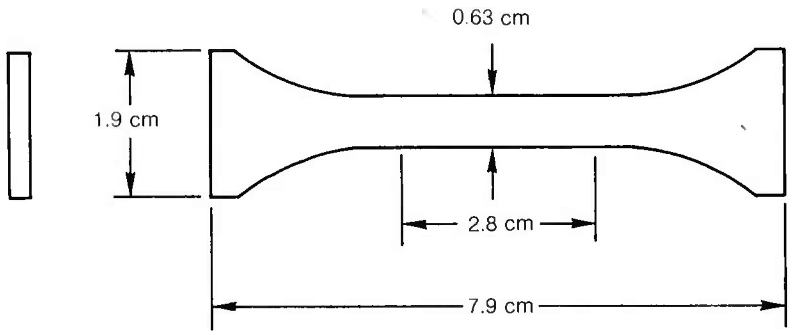
81-4-72-1



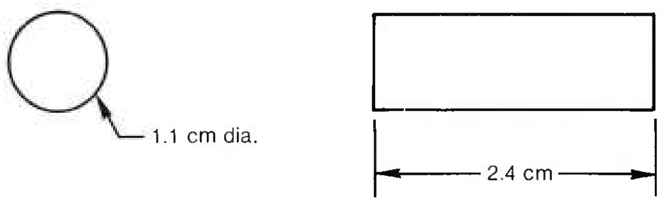
a) TENSILE SPECIMEN WITH DOUBLERS FOR 1 DIRECTION



b) TENSILE SPECIMEN WITH GRIPS FOR 3 DIRECTION



c) COMPRESSION SPECIMEN FOR 1 DIRECTION



d) COMPRESSION SPECIMEN FOR 3 DIRECTION

Figure 3 Test Specimen Configurations

81-4-72-2

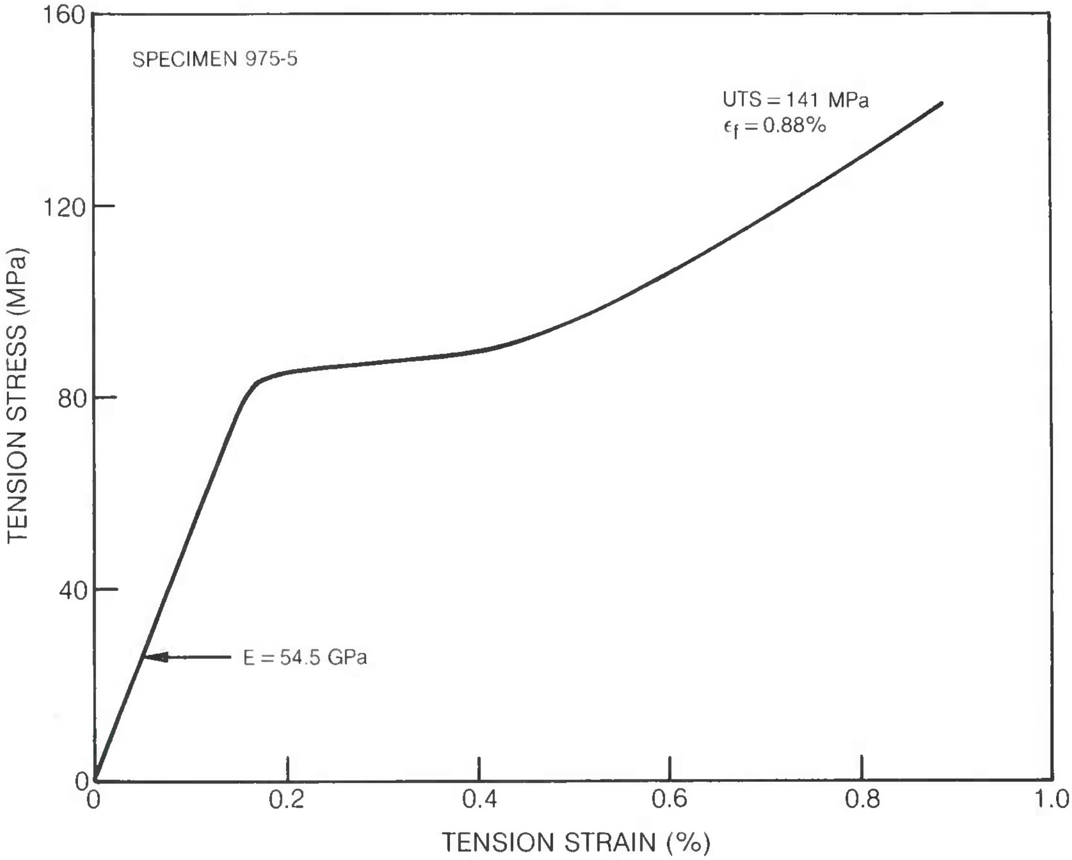


Figure 4 Tension Stress-Strain Curve for the 1 Direction

81-4-72-3

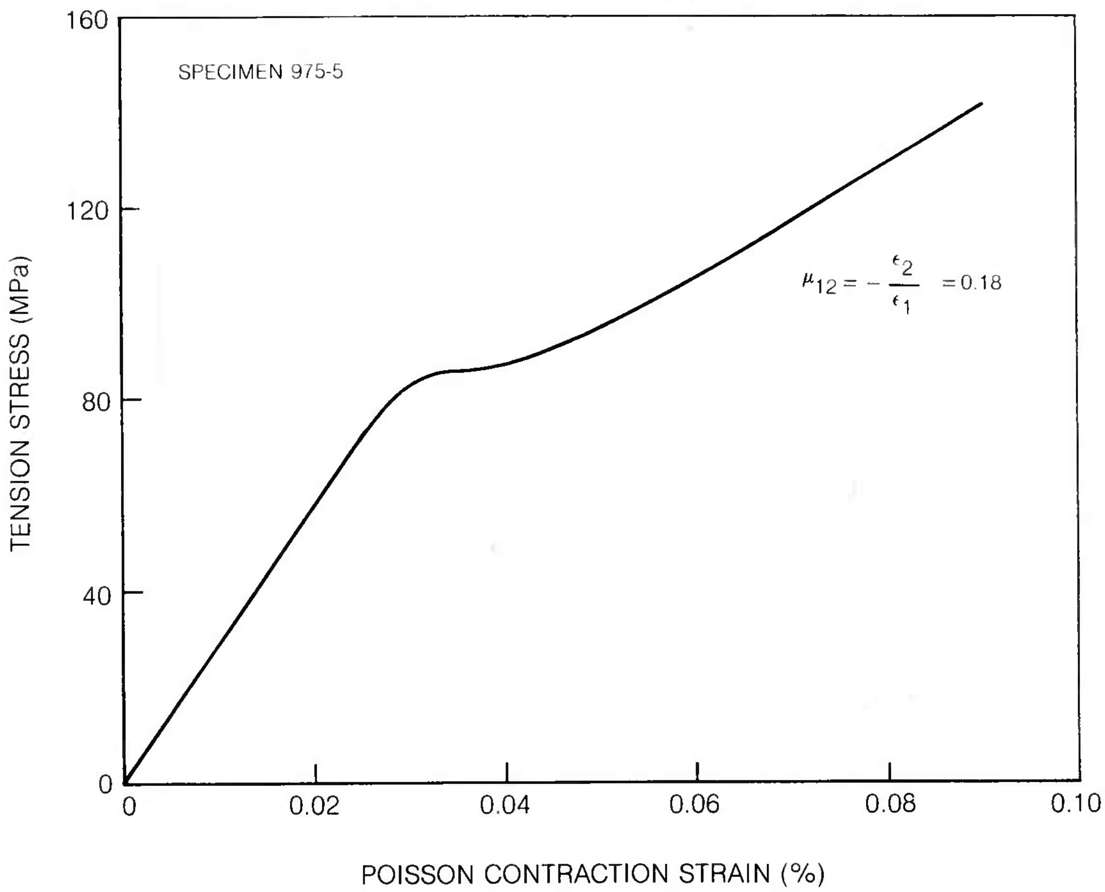


Figure 5 Tension Stress (1) vs Poisson Contraction Strain (2)

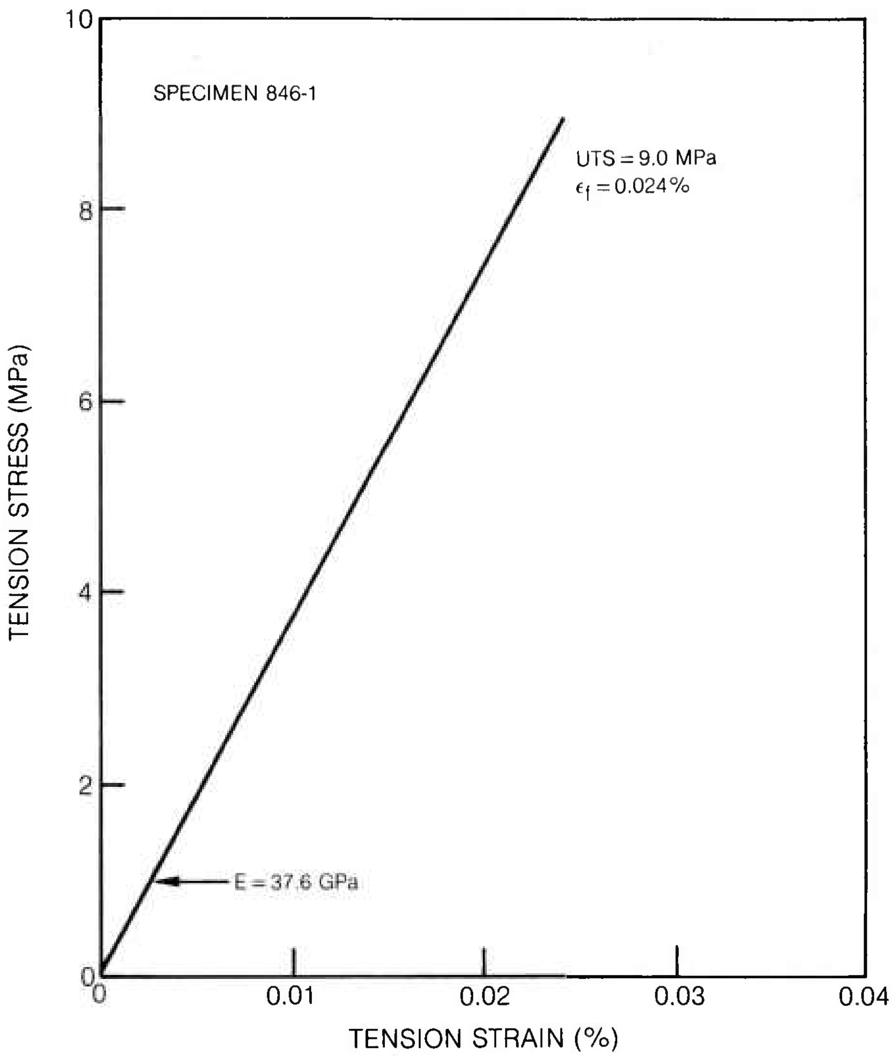


Figure 6 Tension Stress Strain Curve for the 3 Direction

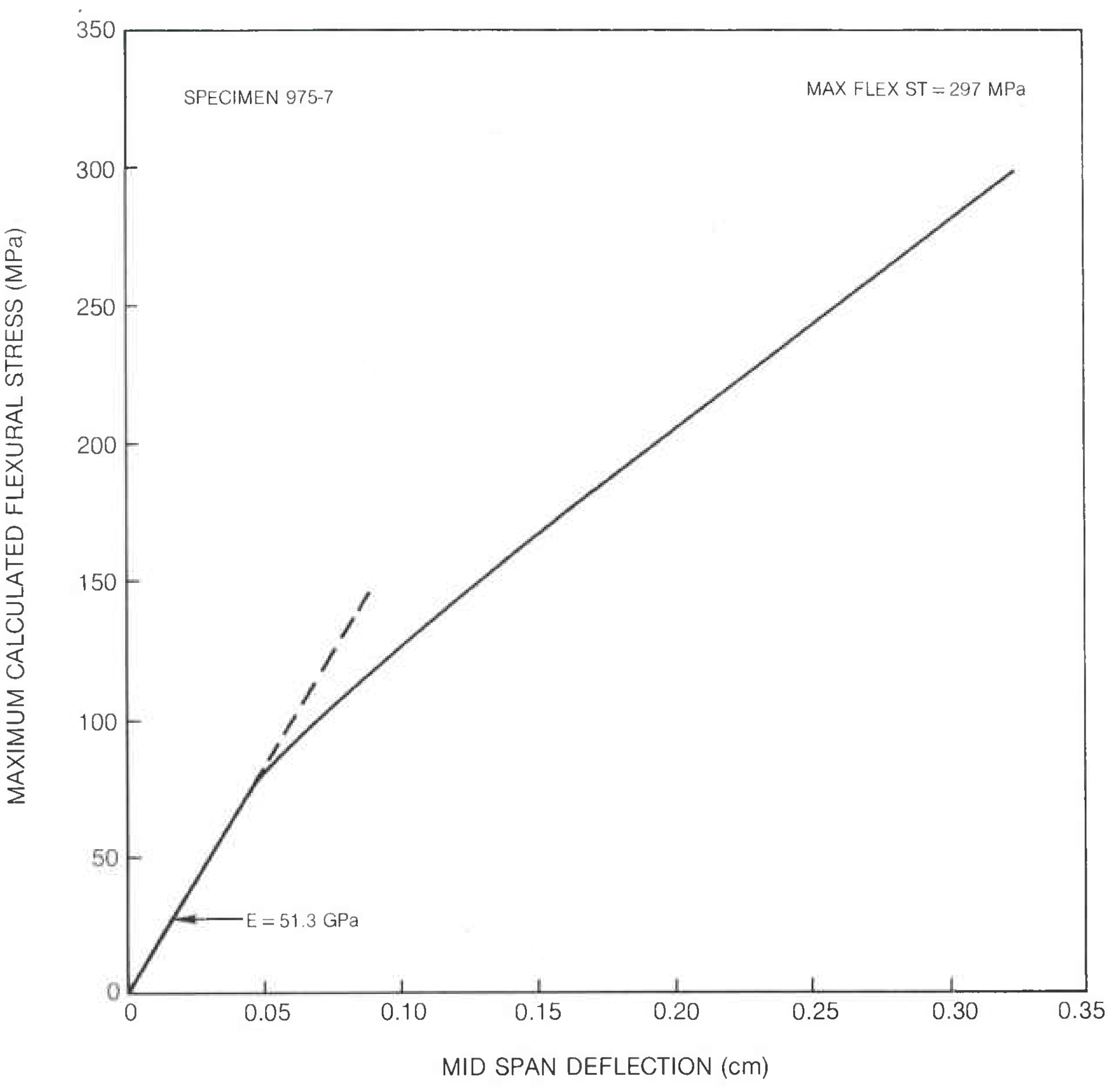


Figure 7 Three Point Bend Curve for the 1 Direction

81-4-72-6

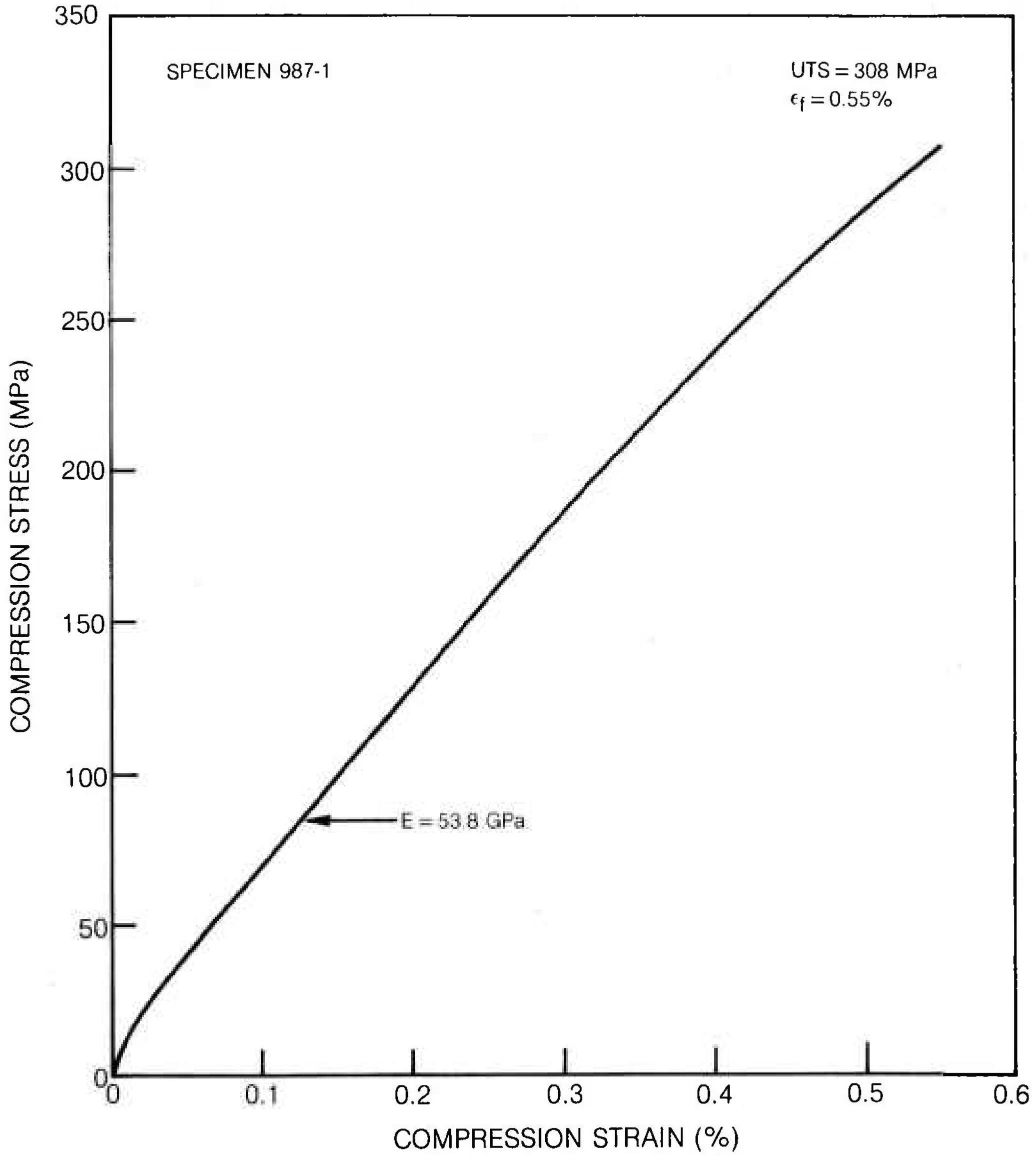


Figure 8 Compression Stress-Strain Curve for the 1 Direction

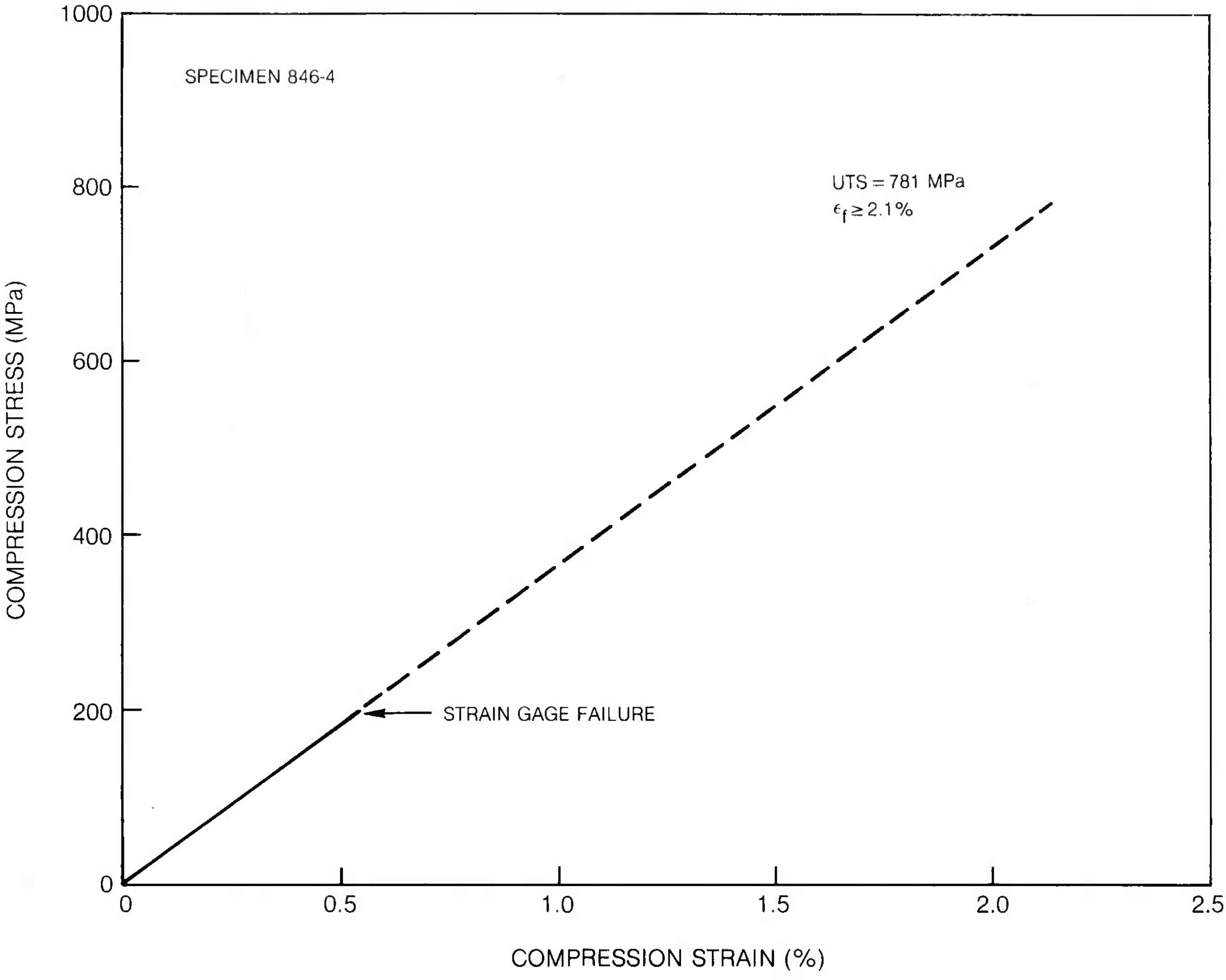
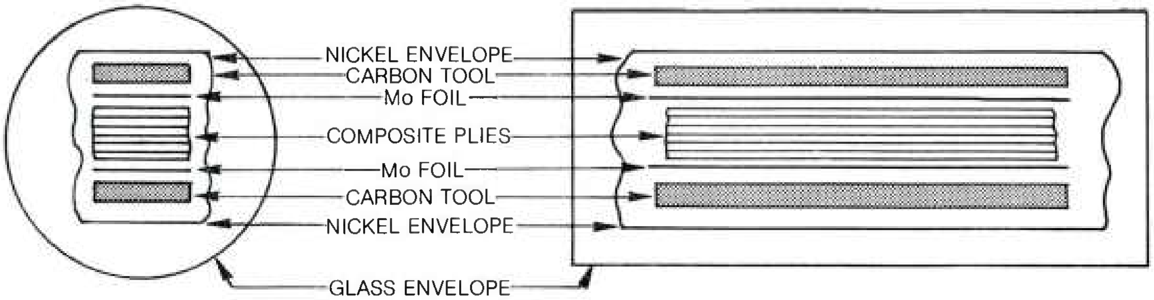
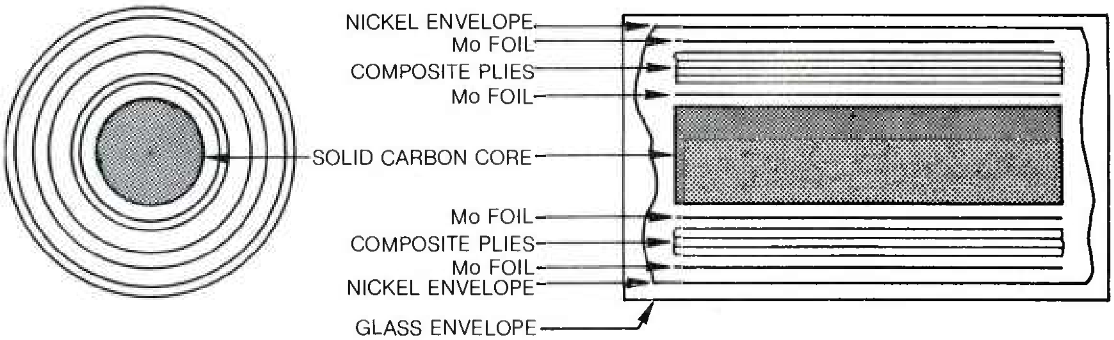


Figure 9 Compression Stress-Strain Curve for the 3 Direction

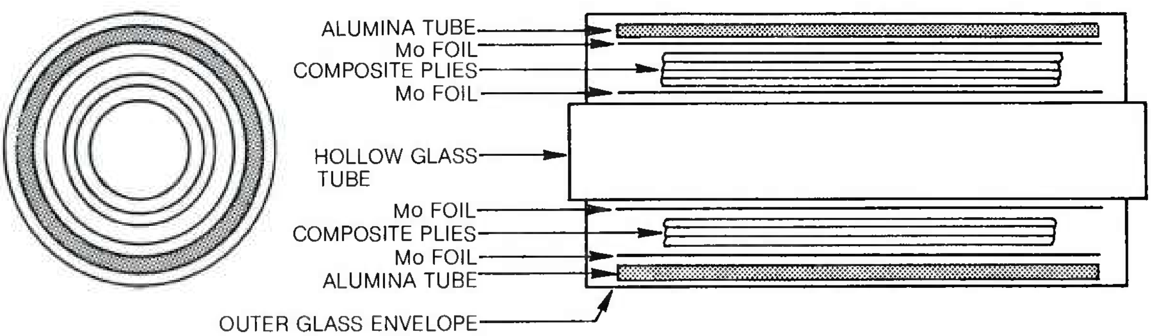
81—4—72—8



a. HIP OF FLAT PLATE

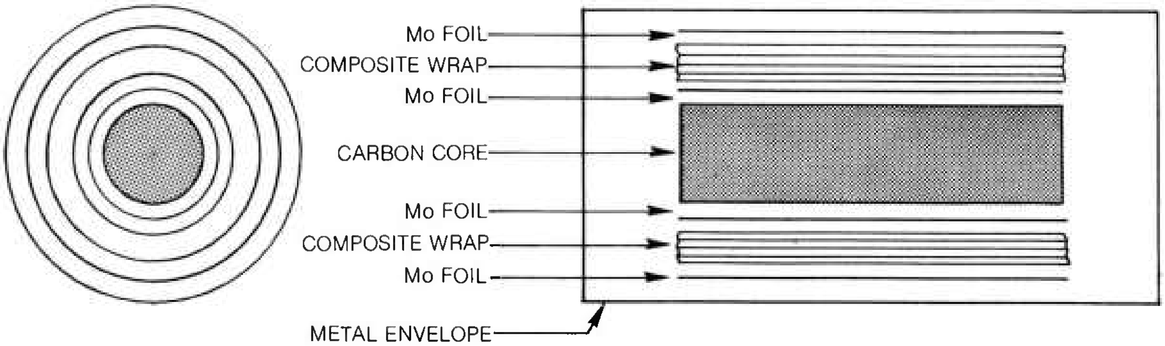


b. HIP OF CYLINDER ON SOLID CORE

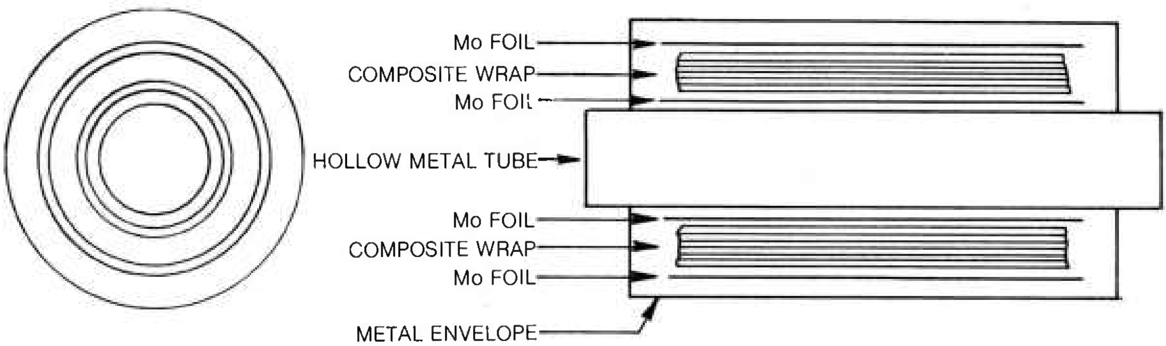


c. HIP OF CYLINDER INSIDE SOLID ALUMINA TUBE

Figure 10 Glass HIP Container Trials



a. HIP OF CYLINDER ON SOLID CORE



b. HIP OF CYLINDER USING HOLLOW METAL CORE

Figure 11 Metal HIP Container Trials

81–5–8–2

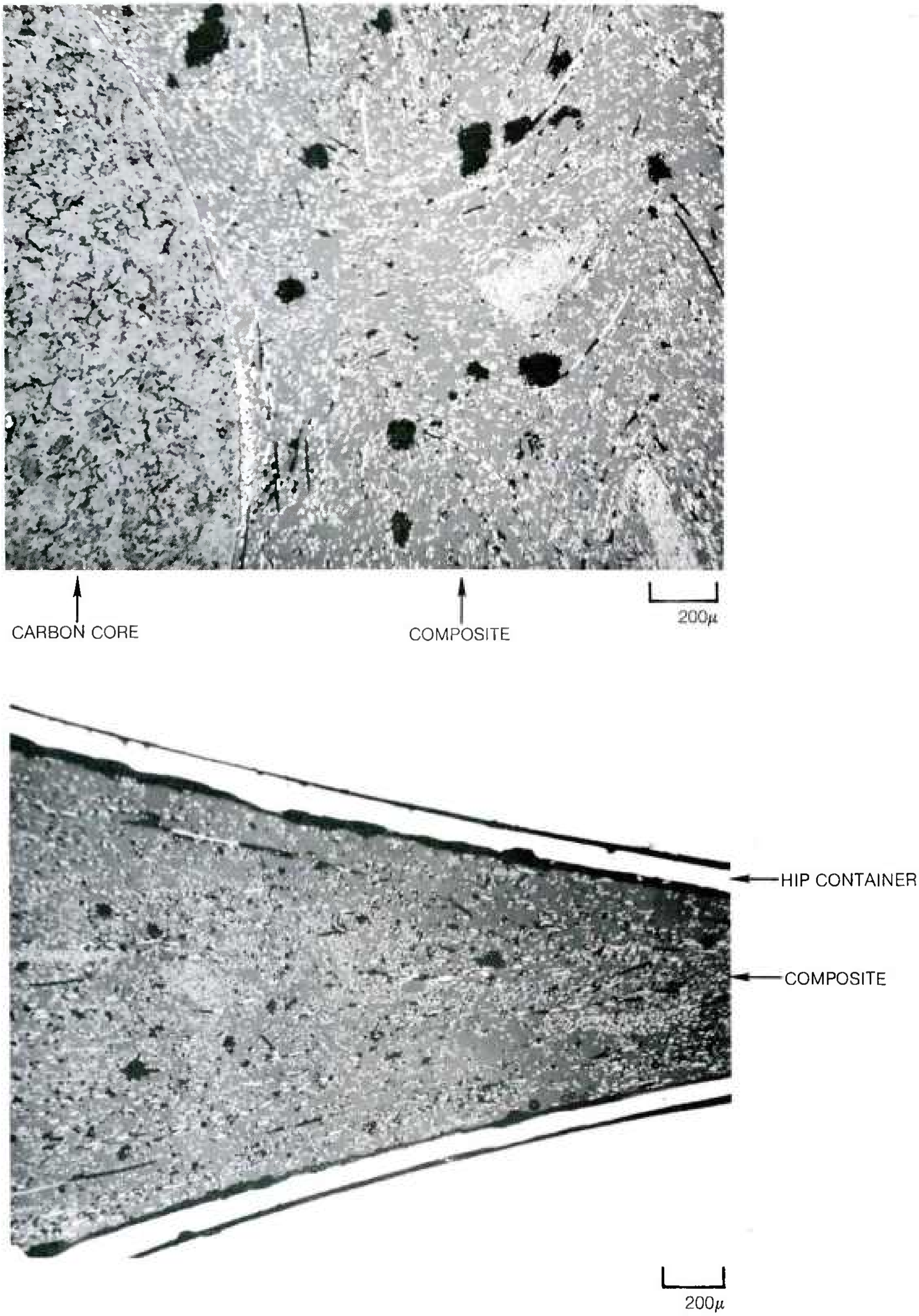


Figure 12 Microstructure Obtained By HIP with a Solid Core

Figure 13 Overall Structure Obtained by HIP with a Hollow Central Metal Tube and Outer Metal Envelope

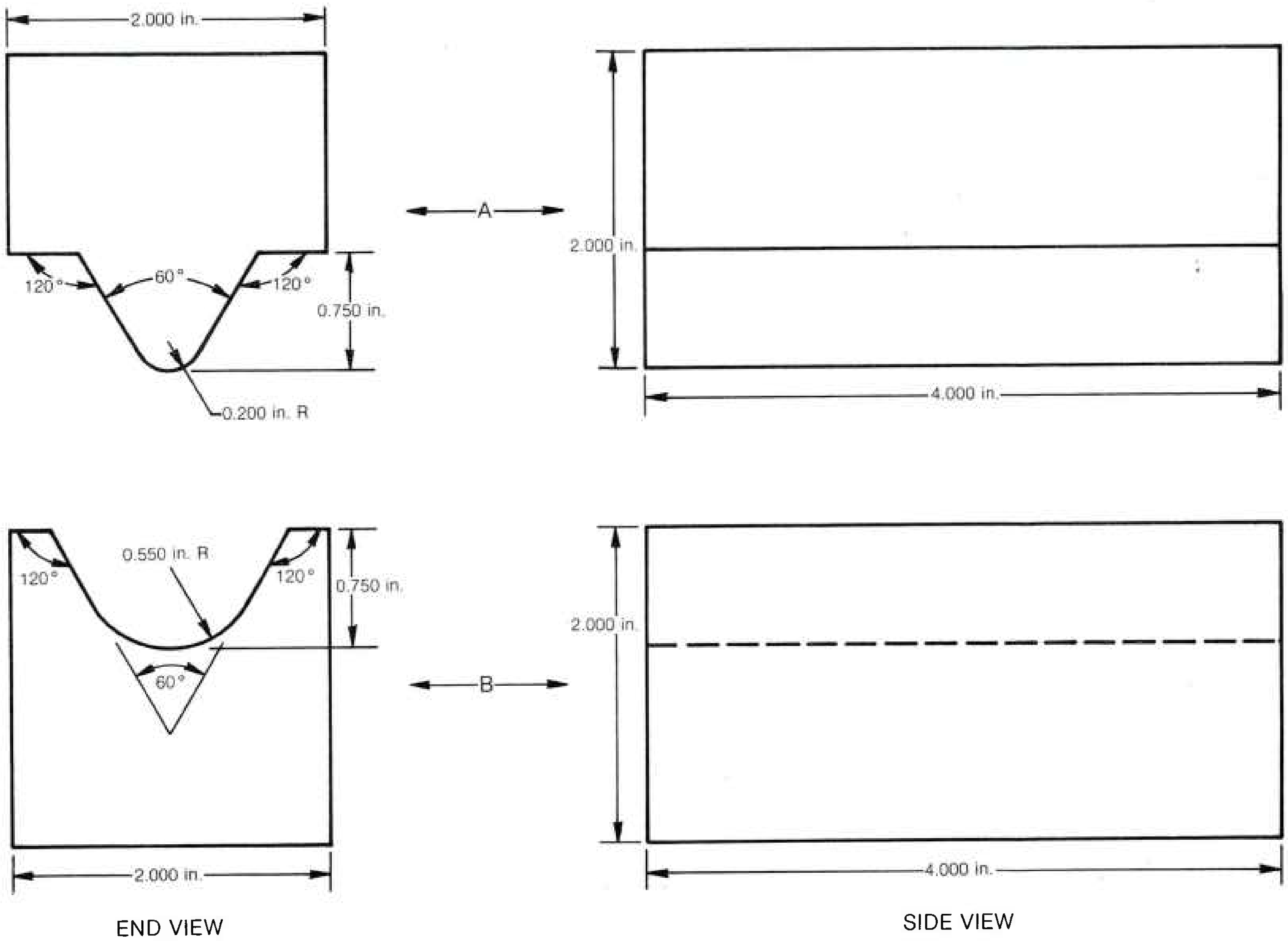


Figure 14 COMPGLAS™ Cylindrical Segment Die Set, (A) Top Plunger, (B) Bottom Plunger

81–4–72–10

Figure 15 Creep Formed COMPGLAS™ Cylindrical Segment

Figure 16 Core Drilled COMPGLAS™ Cylinders

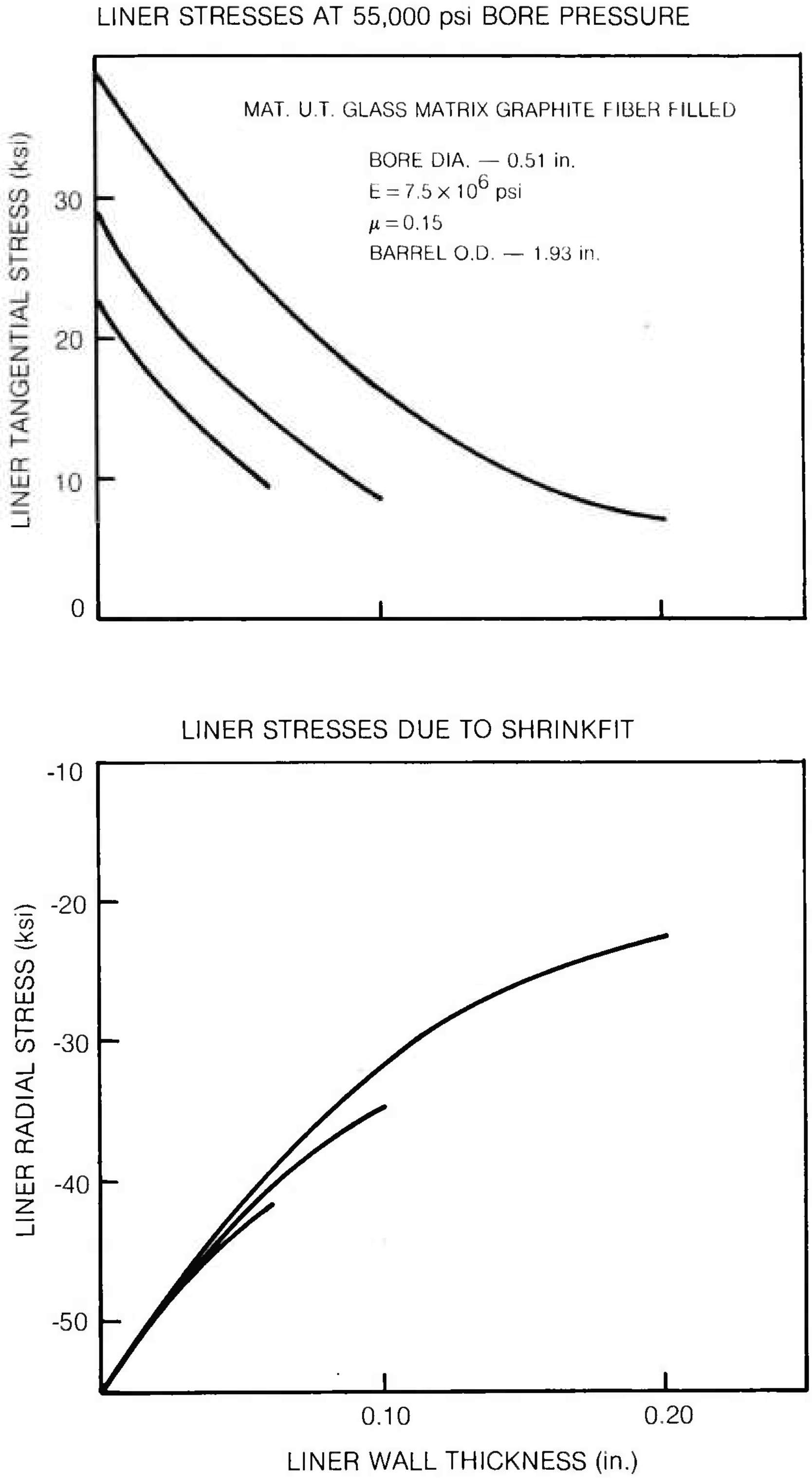


Figure 17. Liner Stress Analysis

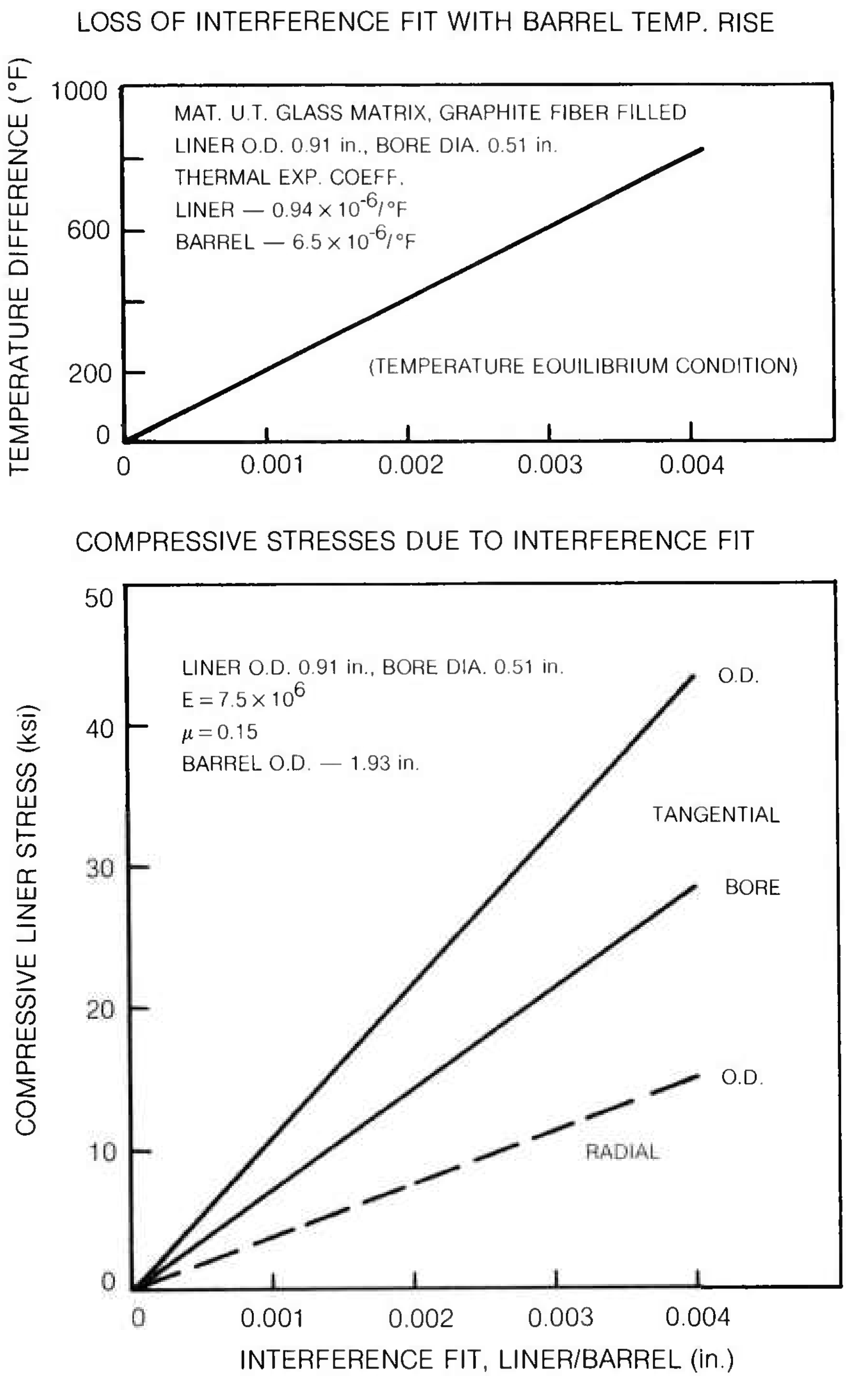


Figure 18. Liner/Barrel Interference Fit Analysis

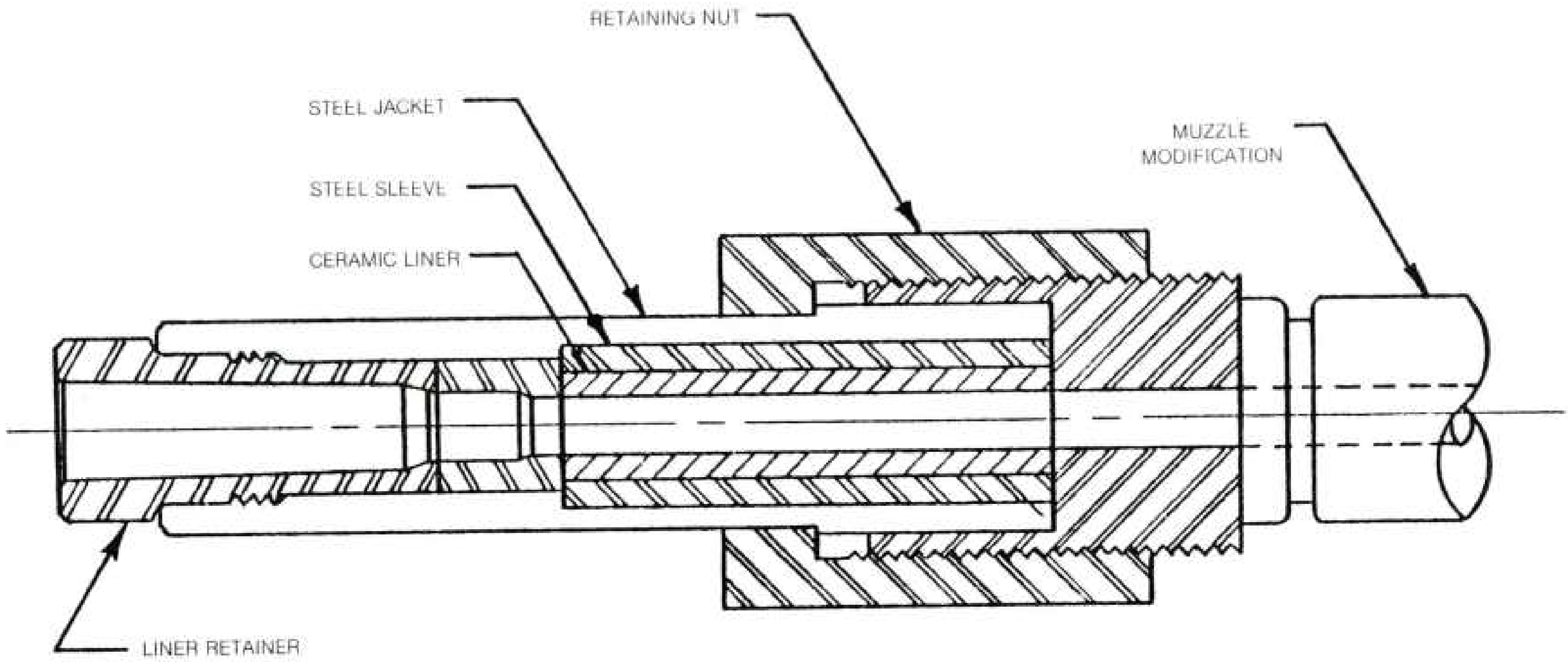
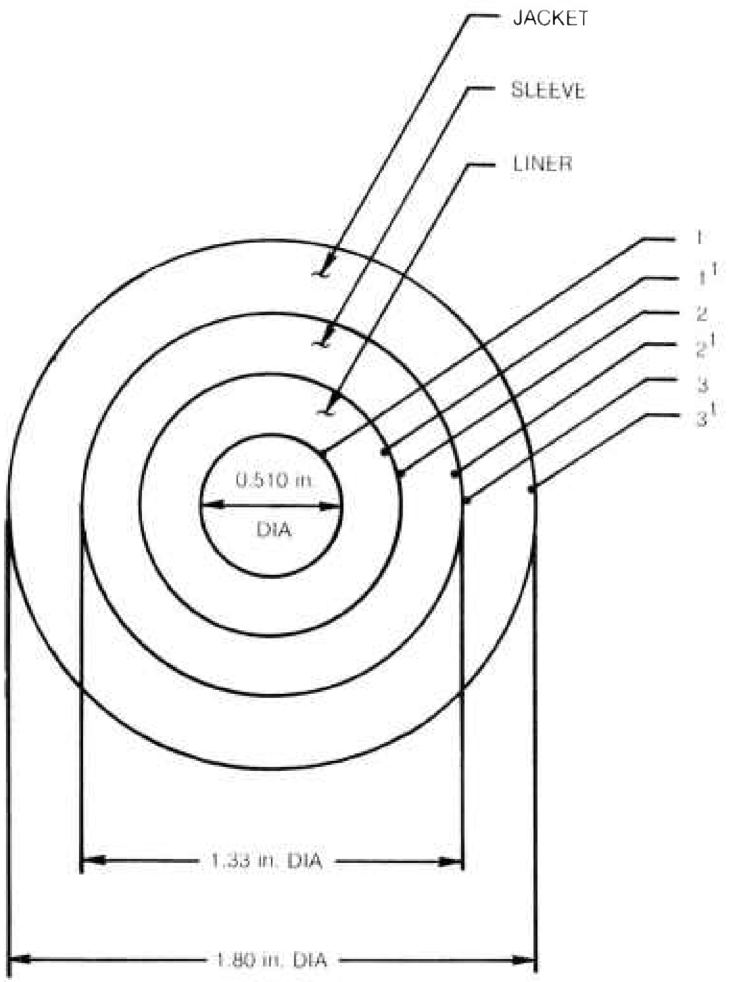


Figure 19. Test Barrel Configuration



P — PRESSURE STRESS
S — STRESS DUE TO SHRINKFIT
R — RESULTANT STRESS

Figure 20. Cross-Section of Barrel Assembly

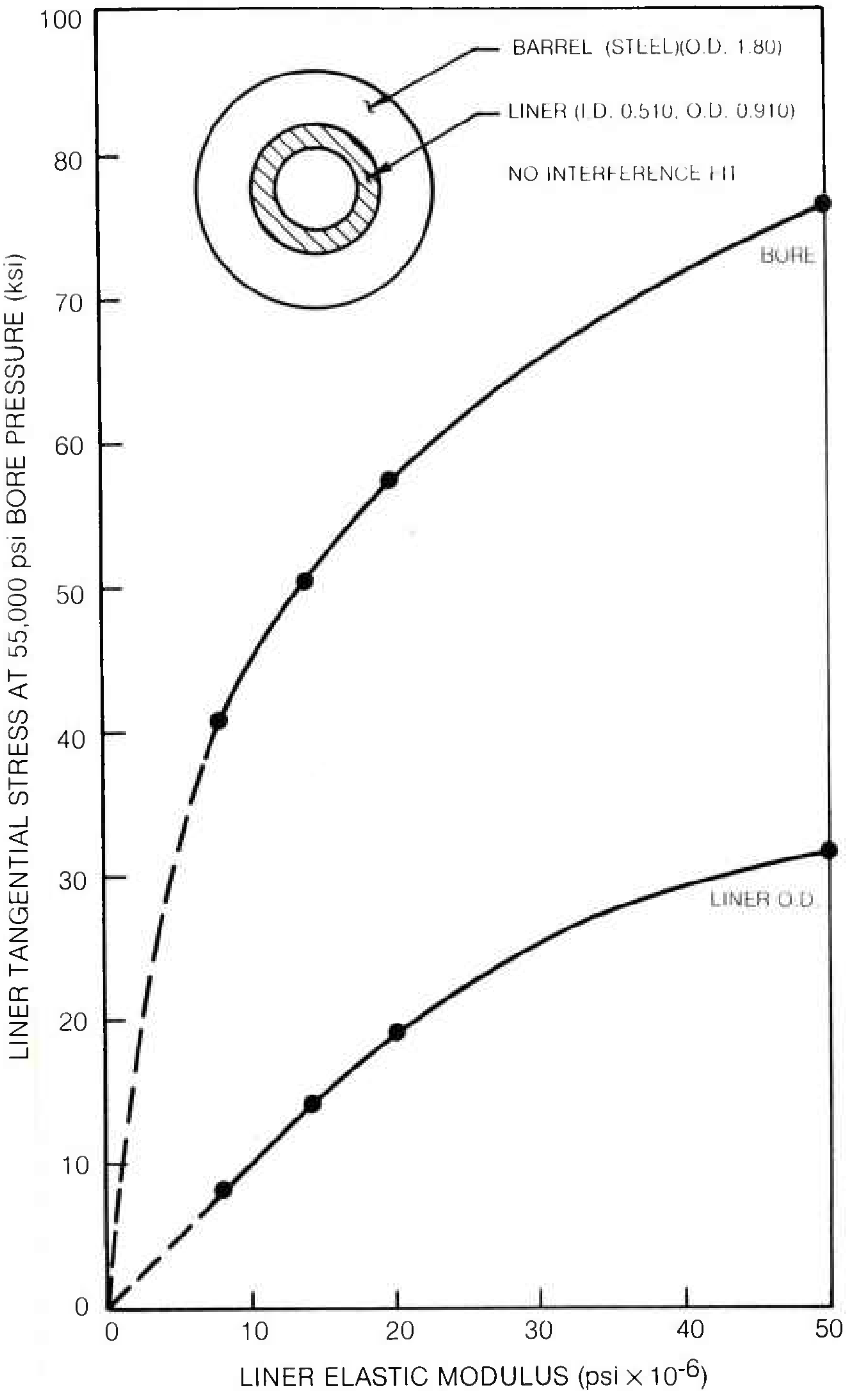


Figure 21. Liner Tangential Stresses vs Modulus of Elasticity

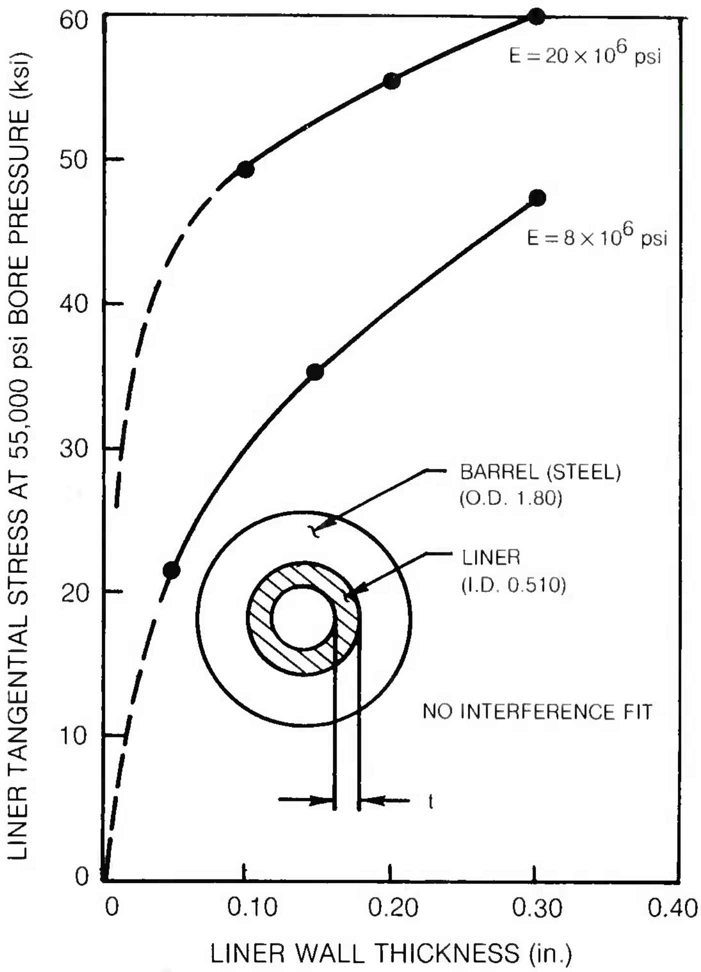
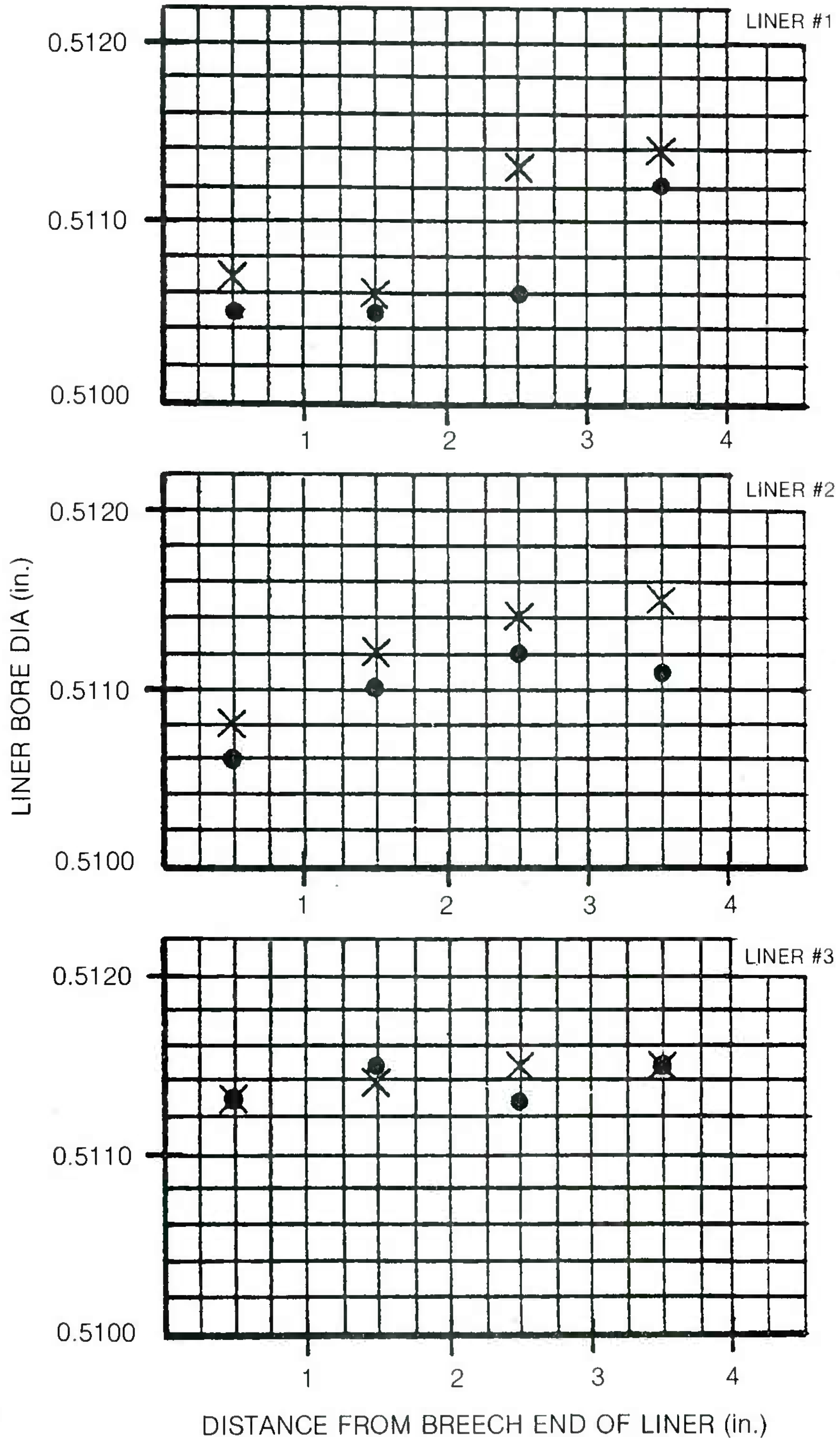


Figure 22. Liner Tangential Bore Stresses vs Wall Thickness and Liner Elastic Modulus

Figure 23. Barrel Assembly #3 After Firing Tests



BEFORE FIRING = ●
AFTER FIRING = X

(PROJECTILE DIAMETER = $0.511^{+0}_{-0.0015}$ in.)

Figure 24. Liner ID Before and After Firing vs Distance from Breech End of Liner

82–1–1–8

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Technical Report AMMRC TR 82-7, February 1982, 55 pp
illus.-tables, Contract DAAG46-81-C-0026
AMCMS Code: 612105.H840011CC
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Key Words

Glass matrix composite
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Graphite fiber
Gun barrel
Mechanical properties
Wear and erosion
Test firing
Hot pressing

The feasibility of fabricating glass matrix composite (COMPGLAS™) cylinders for use as gun barrel liners was investigated. The system of borosilicate glass reinforced with discontinuous graphite fibers was utilized to fabricate three different composite configuration concepts by the fabrication methods of hot isostatic pressing (HIP), uniaxial creep-forming of cylindrical segments, and the machining of cylinders from hot-pressed billets. Analytical design studies performed at the Saco Defense Systems Division of Maremont Corp. indicated that the latter method, where the fibers were randomly oriented in the radial and tangential directions with no fibers in the axial direction, was the most favorable configuration.

Three cylindrical liners were diamond core drilled from the hot-pressed billet, final machined to a .50 caliber bore, assembled into metal sleeves and jackets, and test fired for a total of 10 shots single fire. Although two of the three composite liners showed evidence of a few very small circumferential cracks at one end of the bore before firing, the cracks did not grow as a result of firing. The firing tests indicated that the use of a low modulus, fracture tough, ceramic composite such as graphite fiber reinforced glass is capable of withstanding the pressure stresses resulting from firing without failure and exhibits considerable potential as a gun barrel liner.

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